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DEDICATION

This thesis is dedicated to my parents

PUI-Yu and Yu-Shan.

ABSTRACT

Electrical Muscle Stimulation (EMS) is an effective alternate means for augmenting muscle strength. EMS is commonly associated with perceived discomfort which may subsequently affect its effectiveness. Alternating stimulation current characteristics have influences on the resulting EMS-induced muscle torque and perceived discomfort. The aims of this study were to determine (a) the pulse duration which produced the greatest EMS-induced isometric knee extension torque, (b) the pulse duration which induced the minimal perceived discomfort, (c) the optimal pulse duration which produced maximal EMS-induced torque with minimal perceived discomfort, and (d) the relationship between stimulation current intensity and magnitude of EMS-induced torque.

Twenty-five physical therapy students participated in the study with repeated measures design over the pulse durations of 200, 400, 600, 800, and 1,000 μs. The constant current stimulator, UltraStim®, was used to stimulate subjects' right quadriceps muscles with the knees held at 30° flexion. The stimulation current intensity at all pulse durations was set to the current output meter reading of the stimulator which was the individual maximal tolerable current intensity at 1,000 μs. The frequency of the stimulation current was 50 Hz. The two dependent variables (viz. EMS-induced isometric knee extension torque and perceived discomfort) were measured with the KIN/COM™ dynamometer and the 10-centimeter Visual Analog Scale (VAS) respectively. The stimulation current intensity was found to vary concurrently with the pulse duration. The two dependent variables were therefore standardized with the comparable adjusted current

intensity, which was determined with calibration (i.e. regression) equations of the stimulator involving human skin, at the corresponding pulse duration.

The EMS-induced torques at 600, 800, and 1,000 μs and the perceived discomforts at 800 and 1,000 μs were significantly greater ($p < .05$) than that at 200 and 400 μs. An optimal pulse duration was not found because high EMS-induced torque was associated with high perceived discomfort. However, higher stimulation current intensity yielded stronger EMS-induced torque ($r = .79$, $p < .05$).

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LIST OF ABBREVIATIONS

ACL	Anterior Cruciate Ligament
CTR	Charge - Torque Ratio
EMS	Electrical Muscle Stimulation
I^2R	$Current^2$ x Resistance
MPQ	McGill Pain Questionnaire
MVIC	Maximum Voluntary Isometric Contraction
RMS	Root - Mean - Square
S - D	Strength - Duration
VAS	Visual Analog Scale

CHAPTER ONE

INTRODUCTION

Muscle strength is a construct that can be defined as maximum force or tension generated by a muscle or muscle groups (McArdle, Katch, & Katch, 1986). Muscle strength is a complicated function of which different training methods and different measurement results exist. In well standardized measurements of muscle strength, the standard deviation of the results obtained in repeated tests on the same subjects is of the order of ± 10% or even higher (Tornvall, 1963; Simonson, 1971).

Electrical muscle stimulation (EMS) is an effective means for augmenting muscle strength (Eriksson & Haggmark, 1979; Wigerstad-Lossing, Grimby, Josson, Morelli, Peterson, & Renström, 1988). Cummings (1987) stated that EMS was the application of an electrical stimulus of sufficient intensity and duration to muscle and/or nerve to cause a muscle contraction. The increased popularity of EMS as an alternate approach to traditional progressive-resistive exercise may be attributed to Russian scientist Yadov M. Kots (Currier, 1987). Kots (1977) suggested that (a) EMS-induced contractions produced 10% to 30% greater isometric force than did maximum voluntary isometric contraction (MVIC), (b) EMS based programs resulted in strength improvements of 30% to 40% in already highly trained athletes, and (c) high intensity EMS was associated with a stronger training effect than low intensity EMS. The basis of Kots' claims was that EMS was able to

generate greater isometric force than MVIC. If these claims are true, Kots' suggestions are justified according to the overload principle (McArdle et al., 1986). Despite finding positive training effects of EMS on innervated muscle in various studies (Currier, Lehman, & Lightfoot, 1979; Currier & Mann, 1983; Laughman, Youdas, Garrett, & Choa, 1983; McMiken, Todd-Smith, & Thompson, 1983), many Western researchers have been unable to verify the basis of Kots' claims. Controversy surrounding Kots' claims has been attributed to unavailable details of the Russian technique of EMS and to the insufficient training dose of EMS used by Western researchers, as in Owens and Malone's (1983) study in which lower current intensity, fewer total training sessions, and shorter length of training program than those advocated by Kots were used.

The entire issue regarding the effect of EMS on innervated muscle is complicated by many variations of research design which make many results, strictly speaking, incomparable. Variations of research design include differences in subject parameters (gender, age, activity level), stimulator parameters (output impedance--constant current, or constant voltage), stimulation parameters (current intensity, current on & off [duty] cycle, current modulation), electrode parameters (size, material, couplant, site of placement), training parameters (frequency of training, total training sessions, total contractions in a session, duration of each contraction), and ecological parameters (subject positioning, procedural differences). The central issue concerning EMS is whether it produces a 10% to 30% greater isometric force than a MVIC. Results from Delitto,

Brown, Strube, Rose, and Lehman's (1989), and Selkowitz's (1985) studies support the claim, however, the Delitto et al.'s (1989) study involved a single subject who was an elite weight lifter whose distinct personality and motivation enabled him to take higher current than ordinary subjects and patients were able to take. The low generalizability of the basis of Kots' claims may possibly be accounted for by the sensory discomfort which limited the maximal tolerable current uptake and subsequent torque production (Currier & Mann, 1983; Halbach & Straus, 1980; Kramer, 1987b; Owens & Malone, 1983; Walmsley, Letts, & Vooys, 1984).

As a result, another line of research emerged and was directed towards augmenting the strengthening effect of EMS. Some studies (Hultman, Sjöholm, Jäderholm-EK, & Krynicki, 1983; Kramer, 1987b; McNeal & Baker, 1988; Reisman, 1984; Snyder-Mackler, Garrett, & Roberts, 1989) addressed parameters which would augment torque production while other studies (Baker, Bowman, & McNeal, 1988; Bowman & Baker, 1985; Delitto & Rose, 1986; Gracanin & Trnkoczy, 1975; Vodovnik, Long, Regenos, & Lippay, 1965) addressed minimizing sensory discomfort associated with EMS. However, none of these studies addressed "optimal" parameters that would produce maximal torque production and minimal sensory discomfort.

Statement of Problem

Delitto and Robinson (1989) recommended a pulse duration of 20 to 1,000 μs for a EMS strengthening program. However, while using the wide range of pulse durations, they did not specify the optimal pulse duration(s) necessary in producing maximum torque with minimum sensory discomfort. Few studies have addressed the effect of pulse duration on torque production and sensory discomfort. Baker et al. (1988), Reisman (1984), and Vodovnik et al. (1965) indirectly investigated the effect of pulse duration on comfort (i.e. there was at least one other variable which varied concurrently with pulse duration). Bowman and Baker (1985), and Gracanin and Trnkoczy (1975) directly compared the effect of only two pulse durations on comfort. Alon, Allin, and Inbar (1983) investigated the main and interaction effects of pulse duration and pulse charge on sensory, motor and painful stimulations. Likewise, these studies either addressed "optimal" pulse durations indirectly or did not investigate "optimal" pulse durations that would produce maximal torque and minimal sensory discomfort. Their findings were therefore inconclusive in determining optimal pulse durations.

An important finding concerning pulse duration was the strength-duration (S-D) curve (Figure 1), a graph demonstrating the relationship between current intensity and pulse duration in attaining motor threshold (Benton, Baker, Bowman, & Waters, 1981). Although the basic interpretation of the S-D curve is that higher current intensity (or voltage) is required at shorter pulse durations to reach the same motor threshold, the S-D curve is commonly interpreted beyond its capacity.

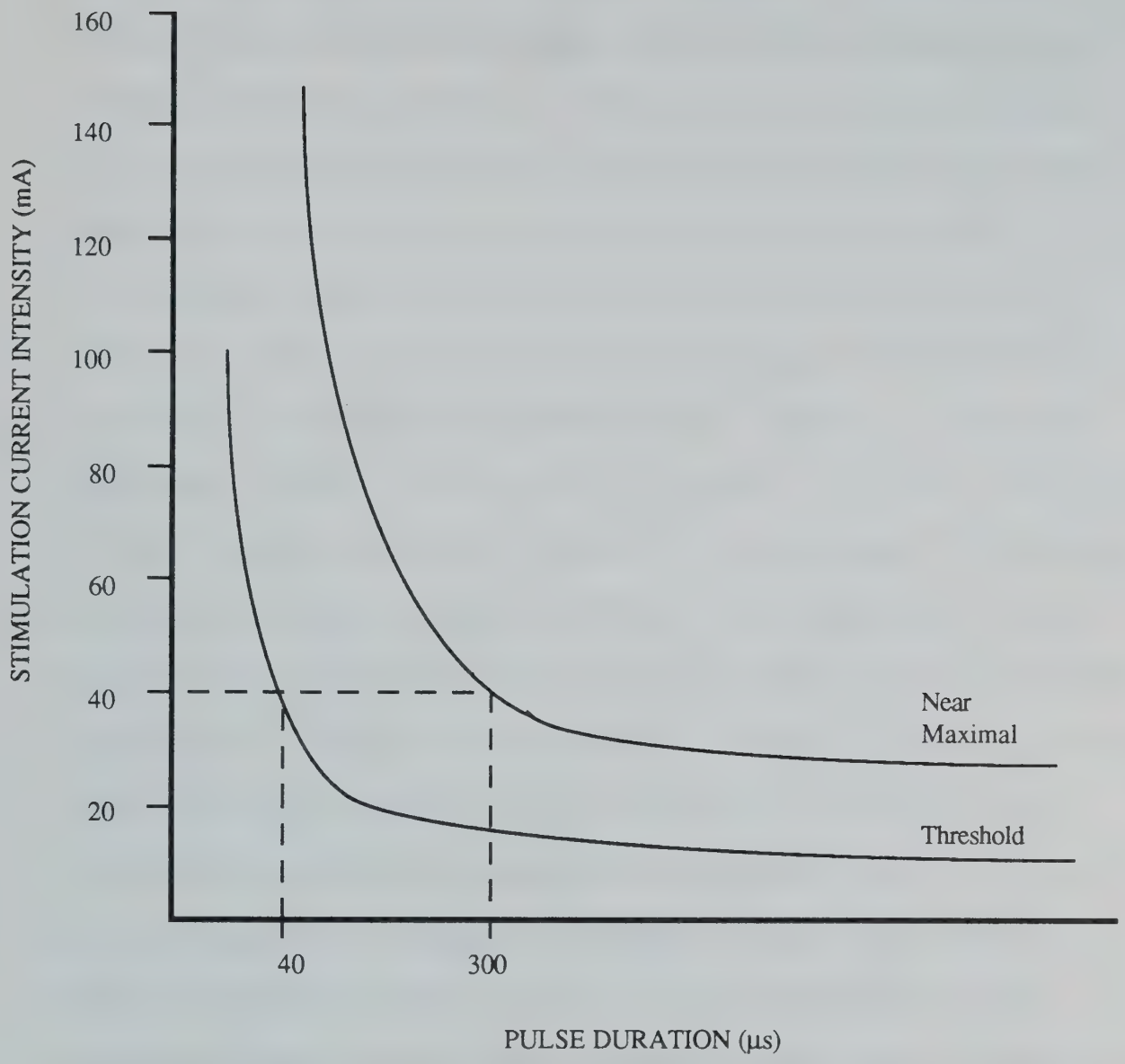

Figure 1. A Strength-Duration Curve of Wrist Extensors (Adapted from Baker, 1981).

Apart from the basic interpretation, Baker (1981) and Benton et al. (1981), when interpreting the S-D curve (Figure 1), found that by maintaining the current intensity at a set level and varying the pulse duration from 300 μs to 50 μs, a motor contraction of near maximal magnitude could be decreased to a just discernible contraction. Such interpretation could easily be misconstrued as a proven positive correlation between pulse duration and magnitude of EMS-induced contraction. The "near maximal" shown in Figure 1 was a criterion determining the dependent variable (stimulus intensity). Using the independent variable (pulse duration) to predict the criterion (magnitude of EMS-induced contraction), however, is not legitimate. In obtaining the S-D curve as the one shown in Figure 1, the magnitude of motor response was transformed into the discrete variable which was decided subjectively by subjects or investigators. The maximal motor response at 40 μs might have been different from that of 300 μs because the S-D curve did not provide any quantitative information about the effect of pulse durations on the magnitude of EMS-induced contraction. In addition, the extent of the influence of sensory discomfort on the magnitude of the maximal motor response may have been different at 40 and 300 μs. By and large, the behavior of the motor response was unclear between the pulse duration from 40 to 300 μs.

The questions of which pulse duration generated greatest EMS-induced torque and which pulse duration caused least sensory discomfort associated with EMS are still unanswered. The scope of the present study concentrated on one of the current characteristics--pulse duration in

augmenting torque production while inducing minimal sensory discomfort.

Subproblem

Baker (1981) reported that the quadriceps muscle responded to the stimulation current intensity with a characteristic S-shaped curve (Figure 2). Figure 2 illustrates that at threshold, a rapid rise in torque occurs such that with small changes in intensity, a disproportionate number of motor fibers are recruited until a plateau is reached. However, Kubiak, Whitman, and Johnston, (1987), Laughman et al. (1983), and Selkowitz (1985) stated in their studies that no consistent correlation was seen between the current intensity and the resulting muscle torque. The discrepancy of their findings cannot be explained as Baker (1981) did not provide details regarding her study.

Lampe and Mannheimer (1984) illustrated that an increased current intensity spread across the nerve structure, progressively recruiting the larger, densely myelinated nerve fibres first (Figure 3). Any further increase of intensity then recruited the smaller pain fibers (Fiber type A∂ and C) nearest the side of entry and thereby causing pain.

Higher current intensity does not necessarily induce stronger muscle contraction (Kubiak et al., 1987; Laughman et al., 1983; Selkowitz, 1985). However, higher current intensity activates pain fibers and results in a more painful sensation. In the presence of pain, the pulse duration

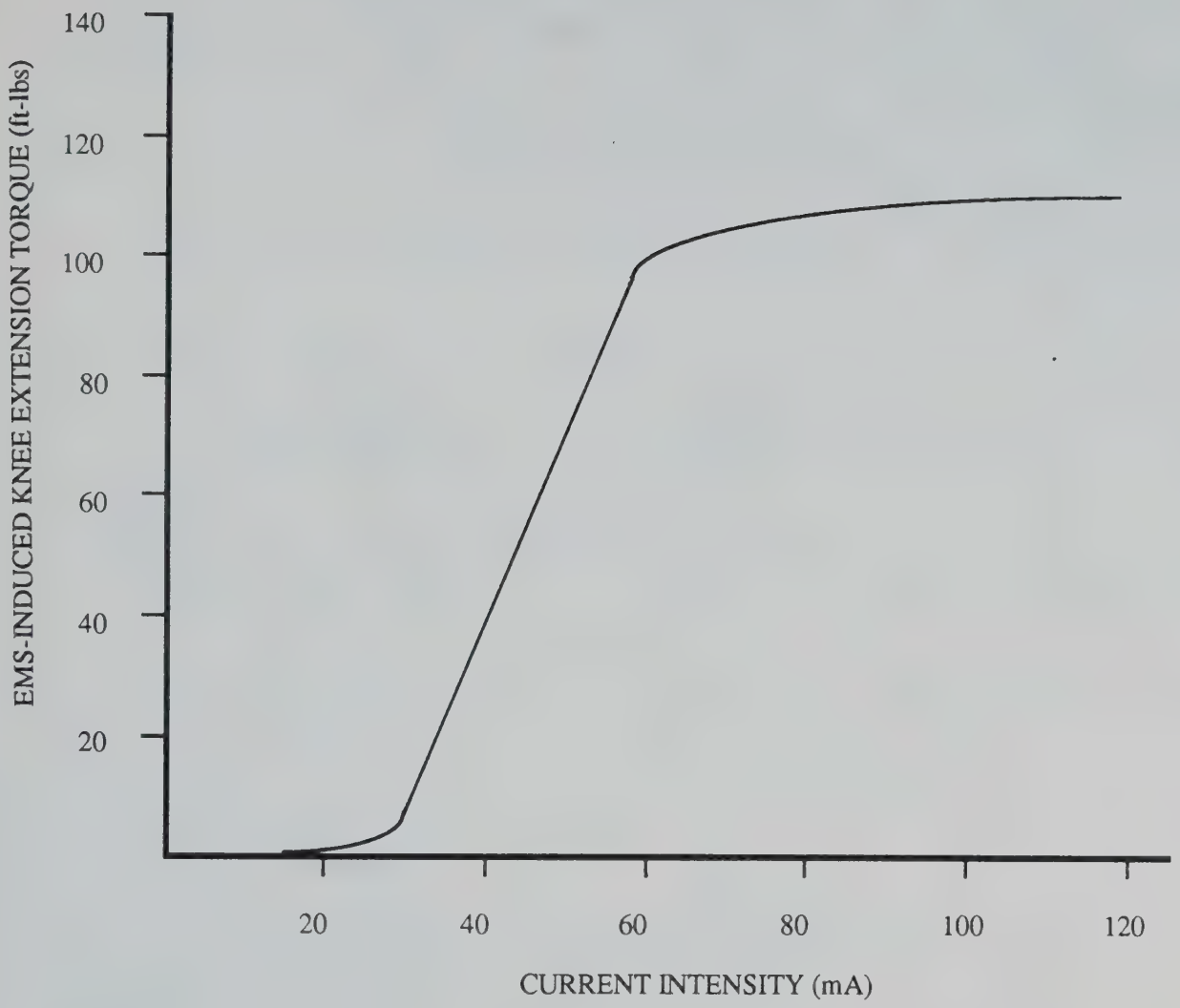

Figure 2. The Relationship between EMS-induced Knee Extension Torque and Stimulation Current Intensity (adapted from Baker, 1981)

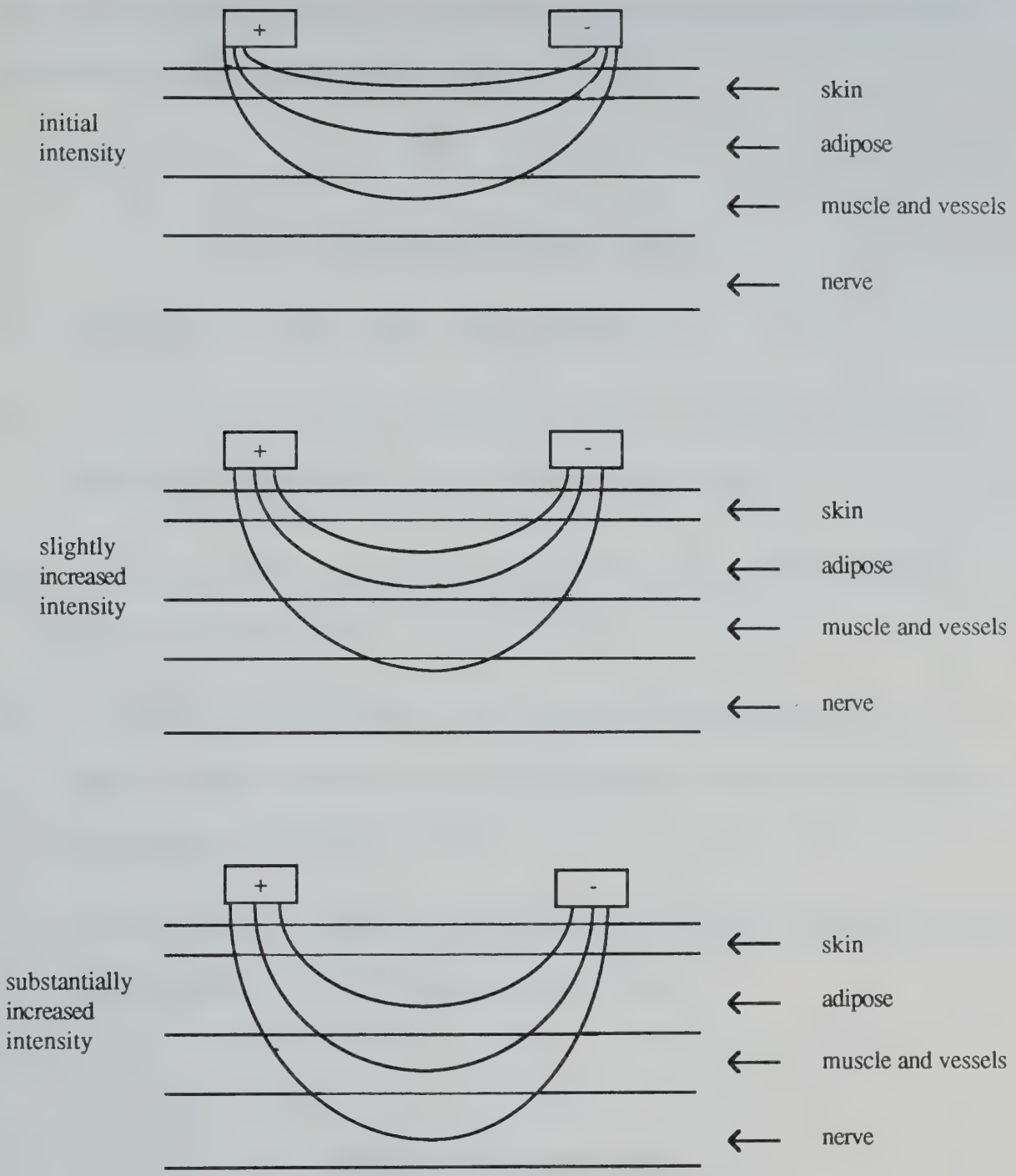

Figure 3. Stimulation Current Intensity and Nerve fiber Recruitment (Adapted from Lampe and Mannheimer, 1984).

may affect the magnitude of the EMS-induced contraction and sensory discomfort disproportionately.

Purposes of the Study

The purposes of the study were as follows:

1. To determine the pulse duration(s) which produced the greatest EMS-induced isometric knee extension contraction.
2. To determine the pulse duration(s) which induced the minimal perceived discomfort
3. To determine the optimal pulse duration(s) which produced maximal EMS-induced torque with minimal perceived discomfort by inductive method.
4. To determine the relationship between stimulation current intensity and magnitude of EMS-induced contraction.

Research Hypotheses

Three hypotheses were tested in the study:

1. There was no difference in the magnitude of the EMS-induced isometric knee extension contraction among the five levels of pulse duration.

2. There was no difference in the perceived discomfort score among the five levels of pulse duration.

3. There was no relationship between stimulation current intensity and magnitude of EMS-induced isometric knee extension contraction.

Delimitations

Delimitations of this study included:

1. Twenty-five informed physical therapy students who have gained previous EMS experience from attending electrotherapy classes during their training.

2. All subjects were male. Gender has been found to have an effect on EMS-induced torque production (Soo, Currier, & Threlkeld, 1988). To eliminate gender as a possible extraneous variable, only male subjects were included in this study.

3. Subject selection criterion, which was based on ethical grounds, included an absence of any orthopedic or neuromuscular disorders of the stimulated leg, chronic systemic disease, dermatologic disease, or expressed fear of or hypersensitivity to EMS. Subjects were excluded for technical reasons if their current tolerances were greater than the output of the stimulator or if they were unable to complete EMS-induced contractions at all pulse durations.

4. Only the right leg was tested. The question of which leg to be stimulated was not a concern in a repeated measures design which was employed in this study. However, by keeping the stimulated side constant, the subsequent variations of ecological parameters and measurement results were minimized. Hence, right leg was arbitrarily selected for stimulation.

5. Volitional and EMS-induced isometric contractions of the quadriceps muscles were examined at 30° from active full knee extension because this angle was commonly adopted in EMS studies (Alon et al., 1985; Hartsell, 1986; McMiken et al., 1983; Owens & Malone, 1983; Strauss & De Domenico, 1986).

6. Stimulation current intensity was limited to subject's tolerance.

7. Surface electrodes for EMS application were used to stimulate the right femoral nerve.

8. Five pulse durations--200, 400, 600, 800, and 1,000 μs were investigated. The majority of studies (Alon et al., 1983; Bowman & Baker, 1985; Gracanin & Trnkoczy, 1975; Vodovnik et al., 1965) concerning the effect of pulse durations on torque production and perceived discomfort were within this range. This fineness of division of pulse duration was appropriate for this preliminary stage of research on "optimal" pulse duration.

9. Stimulation frequency was set at 50 Hz as the literature (Hultman et al., 1983; Kramer, 1987b) showed that 50 Hz was one of the frequencies that augmented torque production.

10. A bidirectional, symmetrical and balanced square wave was used for stimulation because the literature (McNeal & Baker, 1988; Reisman, 1984; Snyder-Mackler, Garrett, & Boberts, 1989) supported that the foregoing waveform was comfortable.

11. A two-minute rest period was allowed between each EMS-induced contraction to avoid local muscle fatigue. Two minutes were sufficient to recover local muscle fatigue (cited by Mundale, 1970)

12. The battery of the stimulator was discarded when its voltage dropped below 95% of the initial voltage (i.e. voltage prior to any usage) or when it had been used for stimulation of five subjects, whichever came first.

Limitations

Limitations of the study included:

1. All subjects were volunteers.

2. The inability to ensure that a subject's volitional contraction was maximal.

3. The inability to ensure that a subject's current intensity tolerance at 1,000 μs was maximal.

4. The inability to control or eliminate the cocontraction of the antagonist muscles.

5. The inability to equalize skin impedance of all subjects, but an attempt was made to lower skin impedance.

6. The inability to align the axis of rotation of the dynamometer lever arm with the instant axis of the knee joint which could not be determined by simple visual method. Not aligning both axes could affect the reliability in torque measurement.

Significance of the Study

The common clinical application of EMS is to strengthen or maintain muscle strength during or following periods of enforced inactivity. Retarding disuse atrophy was significantly more effective when using EMS combined with volitional exercise than exercise alone (Eriksson & Haggmark, 1979; Wigerstad-Lossing et al., 1988). EMS-induced contraction alone was likewise shown to minimize disuse atrophy better than volitional exercise following immobilization (Gould, Donnermeyer, Pope, & Ashikaga, 1982), open meniscectomy (Gould, Donnermeyer, Gammon, Pope, & Ashikaga, 1983), or arthroscopic anterior cruciate ligament (ACL) repair (Morrissey, Brewster, Shields, & Brown, 1985).

The efficacy of EMS in enhancing recovery from disuse atrophy has received much support. Exercise alone was found to be less effective than EMS-induced contraction in recovering strength of the abductor hallucis (LeDoux & Quinones, 1981). The disused ankle dorsiflexor muscles of patients with Duchenne's muscular dystrophy have gained significant strength following nine weeks of EMS (Scott, Vrbova, Hyda, & Dubowitz; 1985).

However, Halkjaer-Kristensen and Ingemann-Hansen (1985) and Sisk, Stralka, Deering, and Griffin (1987) failed to show any significant attenuation of the atrophic process following EMS-induced quadriceps contraction of a post-ACL repair. One of the possible explanations of the non-significant finding is the sensory discomfort associated with EMS. Sensory discomfort seen with the use of EMS is considered to be a significant factor limiting the type of patients, the quality of treatment, and the augmentation of muscle strength (Gracanin & Trnkcozy, 1975; Vodovnik et al., 1965; Halbach & Straus, 1980, Kots, 1977; Kramer & Mendryk, 1982). In order that EMS be effective in increasing strength, it must be capable of producing strong muscle contractions combined with a low pain response (Kots, 1977; Curwin, Stanish, & Valiant, 1980).

Finding the optimal pulse duration(s) is one of the facets for augmenting the effectiveness of EMS in strengthening muscle, thereby reducing medical costs and clinical time (Kramer & Mendryk, 1982). Gould et al. (1983) reported that patients having EMS after open meniscectomy showed a return to usual activity several weeks earlier than control patients. EMS reduced recovery time by as much as one half in

most cases and as little as one-third in the remainder. One might speculate that the optimal pulse duration(s) could contribute to reduce medical costs and clinical time.

Definition of Terms

Balanced/unbalanced (Figure 4d & 4e)

If the area under the first phase of a bidirectional waveform is not the same as the area under the second phase, the waveform is unbalanced. If these areas are equal, the waveform is balanced.

Carrier frequency (Figure 5b)

The number of pulses per second, expressed as Hz. The carrier frequency and pulse rate were synonyms in the present study.

Frequency (Figure 5b)

The stimulation frequency is the number of repeated cluster of pulses per second.

Impedance

The opposition to alternating currents. Impedance takes into account both the capacitative and resistive oppositions to the movement of charged particles. The SI unit of impedance is Ohm (Ω). Skin impedance included skin impedance proper and electrode-skin interface impedance in this study.

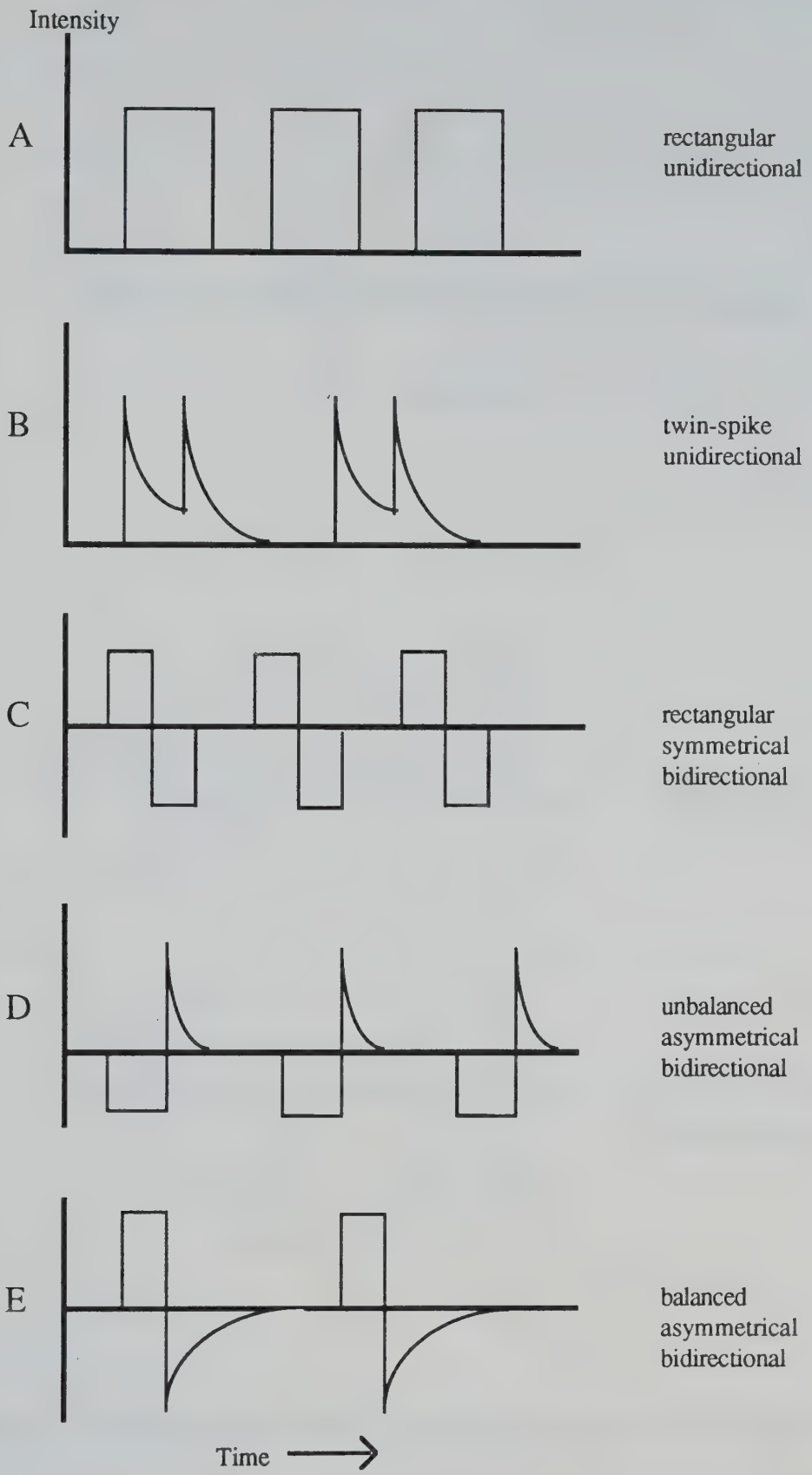

Figure 4. Graphical Representations of Several Waveforms of Stimulation Current (Adapted from Robinson, 1989a).

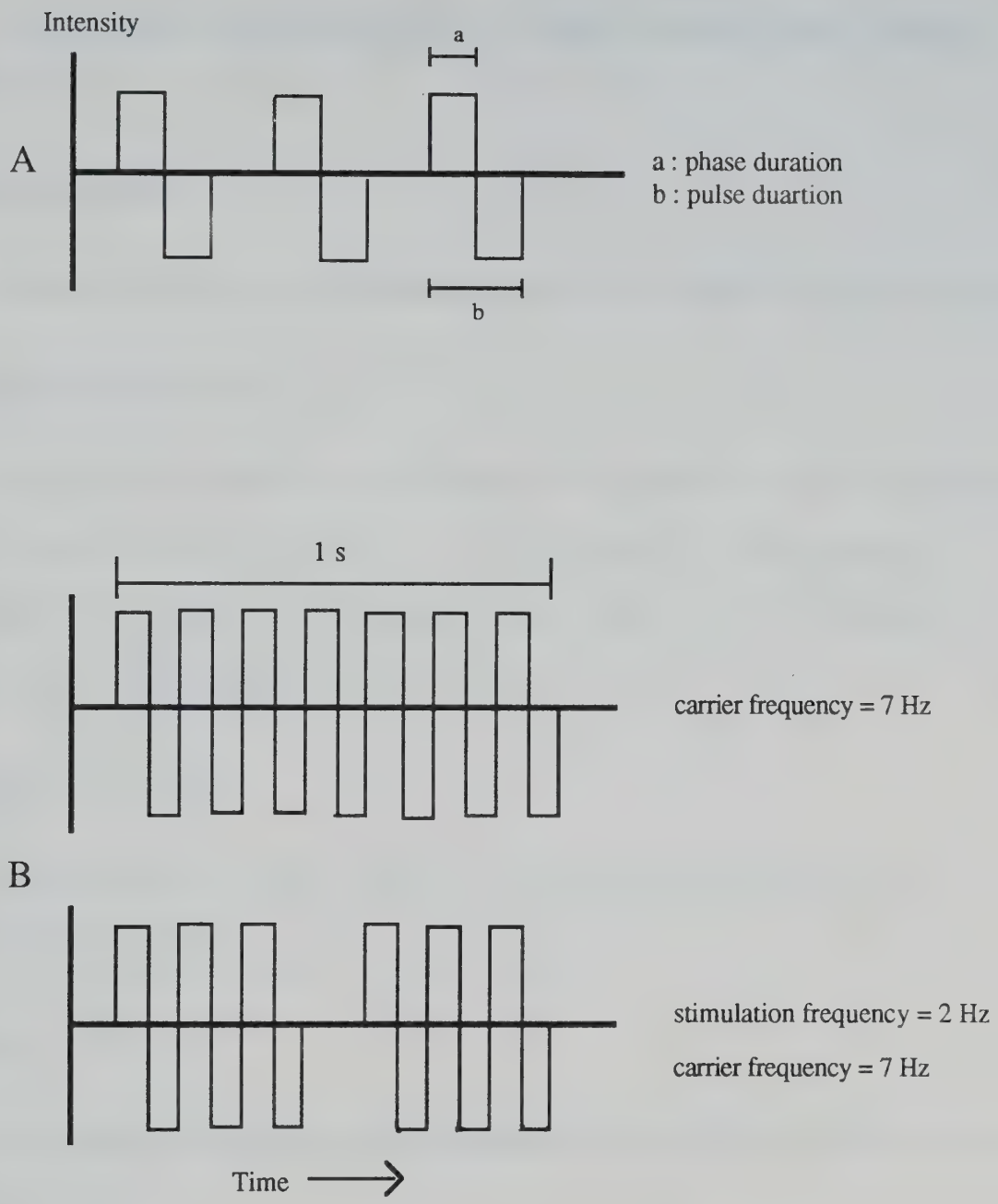

Figure 5. Some Stimulation Current Characteristics (Adapted from Robinson, 1989a).

Maximal tolerable current intensity

The highest amount of electrical current intensity that a subject could tolerate.

Muscle strength

Maximal force or tension generated by a muscle or muscle groups.

Perceived discomfort

Perceived discomfort was defined as a "gestalt" of many feelings and sensations related to the EMS. It was calculated by measuring the distance (cm) from the left margin (zero point) of a 10-centimeter horizontal Visual Analog Scale (VAS).

Phase (Figure 5a)

One-direction current flow on a current intensity/time (or voltage/time) plot.

Pulse

An isolated electrical event separated by a finite time from the next event.

Pulse duration (Figure 5a)

The elapsed time between the beginning and the end of all phases in a single pulse.

Ramp (Surge) modulation

An increase or decrease of pulse intensity to or from peak respectively over time.

Symmetrical/asymmetrical (Figure 4c, 4d & 4e)

If the way in which current intensity varied over time for the first phase of a bidirectional waveform was identical in nature but opposite in direction to the second phase, the bidirectional waveform was referred to as symmetrical.

If the way in which current intensity varied in the first phase of a bidirectional pulse was not the mirror image of the current changes in the second phase, the waveform was referred to as asymmetrical.

Torque

Product of force and the perpendicular distance between the center of rotation and the point of the application of force. The SI unit of torque is Newton-meter (Nm).

Unidirectional/bidirectional (Figure 4a, 4b, 4c, 4d, & 4e)

A pulse which deviated from the zero current line (baseline) in only one direction was called unidirectional.

A pulse which deviated from the baseline first in one direction and then in the opposite direction was called a bidirectional.

Waveform

The shape of the visual representation of current on a current intensity/time (or voltage/time) plot.

CHAPTER TWO

REVIEW OF LITERATURE

Electrical stimulation incorporates the use of electricity to obtain desired physiologic responses for the assessment or care of diseases and injuries in humans (Nelson & Currier, 1987). Electrical stimulation has been used for centuries by the medical profession for therapeutic and diagnostic purposes (Geddes, 1984). EMS is the application of an electrical stimulus of sufficient intensity and duration to muscle and/or nerve in order to produce a muscle contraction (Cummings, 1987). The common applications of EMS in rehabilitation are (a) to retard muscle atrophy and to strengthen muscle atrophied from immobilization, disuse or pain, (b) to facilitate muscle re-education, (c) to maintain range of motion thereby preventing joint contractures, (d) to inhibit spasticity, and (e) to provide orthotic support to a joint (Baker, 1981; Ferguson, Blackley, Knight, Sutlive, Underwood, & Greathouse, 1989; Wong, 1986).

The spark which ignited widespread interest in EMS did not come until the mid-1970s. In 1976, at the Olympic Games in Montreal, Soviet athletes were observed using EMS in conjunction with voluntary exercise as a strength training technique (Delitto & Robinson, 1989). In 1977, Kots of Russia reported that EMS might produce muscle strength gains in elite athletes which were 30% to 40% greater than those achieved through exercise alone. These dramatic strength gains were achieved by eliciting muscle contractions which were 10% to 30% greater than those achieved by

MVIC. Western researchers soon initiated studies designed to verify Kots' claims. Most of these studies addressed whether (a) EMS was effective in strengthening normal muscle and (b) EMS was more effective than other methods in strengthening normal muscle.

Training Effect of EMS in Normal Muscle

By far, the commonest research design for investigating the training effect of EMS has been the "10:50:10 format" which was described as "standardized" by Hartsell (1986) and Kramer and Mendryk (1982). This format involved 10 EMS-induced isometric contractions of 10-second duration each, followed by a 50-second rest period, thereby constituting one treatment session.

Three studies (Currier & Mann, 1983; Kubiak et al., 1987; Laughman et al., 1983) used the same type of electrical stimulator--Electrostim 180 and the 10:50:10 protocol used by Kots to train subjects' quadriceps muscles for five weeks. The differences among the studies were the total number of training sessions and the stimulation current intensity (Table 1). They reported 16.6% to 33% poststimulation strength gains in MVIC. Significant increases for the stimulation groups were found when the posttest MVIC was compared between stimulation and control groups.

Selkowitz (1985), and Soo et al. (1988) also used the Electrostim 180 (Table 1). Selkowitz (1985) trained the stimulation group with maximal tolerable current intensity three days a week for four weeks and found that

Table 1. Summary of selected studies of the training effect of EMS

Parameter	Study						
	Currier et al. (1979)	Currier & Mann (1983)	Kubiak et al. (1987)	Laughman et al. (1983)	McMiken et al. (1983)	Selkowitz (1985)	Soo et al. (1988)[a]
Waveform	rectangular	sine	?[b]	sine	faradic	sine	sine
Pulse duration	?	100 μs	?	100 μs	100 μs	?	?
Stimulation frequency	25 Hz	50 Hz	?	50Hz	75 Hz	50 Hz	50 Hz
Current intensity	Tolerable I_{max}[c]	60% MVIC	at least 45% MVIC	Tolerable I_{max}	at least 80% MVIC	Tolerable I_{max}	50% MVIC
Training format[d]	6:10:6	10:50:10	10:50:10	10:50:10	10:50:10	10:120:10	10:?:8
Total training sessions	10	15	15	25	10-12	12	10
Post-test MVIC gain[e]							
Control group	2.1%	1.6%	8.0%	2.0%	N.A.[f]	14.7%	-5.8%
Stimulation group	N.A.	16.6%	33.0%	22.0%	21.9%	40.3%	24.1%
Exercise group	23.3%	34.4%	43.5%	18.0%	25.1%	N.A.	N.A.
Super-imposed group[g]	26.3%	23.5%	N.A.	N.A.	N.A.	N.A.	N.A.

[a] Only male subjects results were reported in this table [b]Not clearly documented in the study. [c]Maximal tolerable current intensity. [d]The duration of each contraction [ramp time was not taken into account]:the duration of rest period between contractions:the total contractions. [e]Absolute difference between pre & posttest scores, expressed as a percentage of the pretest score. [f]Not Applicable. [g]Group trained with concurrent combination of MVIC and EMS.

the increase of poststimulation MVIC was 40.3%, thereby being significantly greater than that of the control. Soo et al. (1988) used current intensity that produced 50% of MVIC to stimulate subjects' quadriceps two days a week for five weeks in which the electrical stimulation was repeated eight times per session. They reported a 24.1% increase of poststimulation MVIC in male subjects.

Studies (Fahey, Harvey, Schroeder, & Ferguson, 1985; Hartsell, 1986; Lai, De Domenico, & Strauss, 1988; Romero, Sandford, Schroeder, & Fahey, 1982; Wolf, Ariel, Saar, Penny, & Railey, 1986), which had incomparable research designs, measured isometric and isokinetic peak torques, girth, endurance or functional parameters in relation to effect of electrical stimulation. These studies revealed that the posttest measurements of the stimulation groups had significantly improved in strength compared to that of the control groups.

Owens and Malone (1983), and Mohr, Carlson, Sulentic and Landry (1985) used sinusoidal and unidirectional twin peak waves respectively to stimulate subjects' quadriceps as tolerated for 10 isometric contractions in each session. Subjects in Owens and Malone's (1983) study received the 10:50:10 format of stimulation on either consecutive or alternate days for 10 days, while those in Mohr et al.'s (1985) study had a 10:10:10 format of stimulation five times a week for three weeks. Both reported no significant difference in posttest MVIC between stimulation and control groups. However, the total number of training sessions in Owens and Malone's (1983) study was 5 or 10 sessions which was comparatively lower than the 10-15 sessions of those studies (Currier & Mann, 1983; Kubiak et al., 1987;

Selkowitz, 1985) claiming a positive stimulation effect. The current used by Owens and Malone (1983) was interrupted every 10 ms for 50 ms with stimulation frequency of 16.8 Hz which was also low compared to the foregoing studies (Currier & Mann, 1983; Kubiak et al., 1987; Laughman et al., 1983; Selkowitz, 1985; Soo et al. 1988) in which the current was interrupted every 10 ms for 10 ms with a stimulation frequency of 50 Hz. The insignificant finding from Mohr et al.'s (1985) study could potentially be attributed to the "low" maximum output capacity of the electrical stimulator which subjects were able to tolerate within the first three stimulation sessions. Furthermore, the 10-second rest between contractions was low compared to the commonly used 50-second rest as in Currier & Mann's (1983), Kubiak et al.'s (1987) and Laughman et al.'s (1983) studies.

In order to compare the effectiveness of EMS and exercise, four studies (Currier & Mann, 1983; Kubiak et al., 1987; Laughman et al., 1983; McMiken et al., 1983) included exercise groups which performed the MVIC of knee extension as a treatment protocol (Table 1). The total number of contractions and total contraction time were standardized for both stimulation and exercise groups. McMiken et al.'s (1983) study differed from the other three studies in that McMiken et al. (1983) used faradic current producing torque up to 80% MVIC to train subjects four days a week for three weeks while the other three studies used an interrupted sine wave at different current intensities (Table 1). The posttest MVICs for the stimulation groups of the four studies increased by 16.6% to 33.0% while the exercise groups increased by 18% to 43.5%. In summary, no significant difference in

posttest MVIC was noted between exercise and electrical stimulation groups in any of the four studies. However, Mohr et al. (1985) reported that the posttest MVIC of the isometric exercise group (14.7%) was significantly higher than the stimulation group (0.7%). As mentioned before, Mohr et al.'s (1985) finding might be accounted for by the insufficient dose of the "low" maximum current capacity of the stimulator or by the fatigue effect resulting from the short rest period between contractions for the stimulation group.

The additive effect of electrical stimulation and isometric exercise has been investigated by Currier et al. (1979), and Currier and Mann (1983). Both studies included an experimental group which performed MVIC while simultaneously receiving electrical stimulation. Currier and Mann (1983) used the 10:50:10 format while subjects in Currier et al.'s (1979) study received six 6-second contractions with 10-second rest between contractions. The posttest MVIC of the experimental groups increased by 26.3% and by 23.5% in Currier et al.'s (1979) and Currier and Mann's (1983) studies respectively (Table 1). Both studies agreed that the electrical stimulation superimposed with isometric contraction was as effective as, but not more effective than, isometric exercise alone.

Two studies (Halbach & Straus, 1980; Nobbs & Rhodes, 1986) attempted to compared the effectiveness between EMS and isokinetic training. Both trained subjects isometrically in the stimulation groups and concentrically in the isokinetic group. Halbach and Straus (1980) showed that there was a 42% and 22% increase in posttest isokinetic peak torque at 120°/s for the isokinetic and stimulation groups respectively. By equating

every second of EMS to an isokinetic repetition in attempting to equalize the dose of the two treatments, Halbach and Straus (1980) concluded that isokinetic training was superior to EMS training in increasing power. Nobbs and Rhodes (1986) reported a significant difference between pre and posttest isometric peak torque and isokinetic peak torque at 30°/s in all treatment groups, yet no difference was noted among treatment groups. Nobbs and Rhodes (1986) did not equalize the dosage of the treatments by either the total number of contractions or the total contraction time. Based on these research designs, the findings of the two studies were not conclusive.

In summary, it appears that EMS is able to strengthen the normal muscle. However, its superiority over other training methods has yet to be proven.

Current Characteristics Augmenting Torque Production

In order to enhance physiological function effectively and to produce a training effect, a specific exercise overload must be applied. The overload effect can be achieved by manipulating combinations of training frequency, intensity, and duration. McArdle et al. (1986) stressed that strength improvements were generally governed by the intensity of overload and not by the specific method. As a general rule, a muscle working close to its maximum force-generating capacity will increase in strength.

Current Intensity

Studies regulated the training intensity by administering current intensity either to subjects' maximal tolerance (Currier et al., 1979; Halbach & Straus, 1980; Hartsell, 1986; Laughman et al., 1983; Mohr et al., 1985; Nobbs & Rhodes, 1986; Owens & Malone, 1983) or to generate certain percentage of MVIC (Currier & Mann, 1983; Kubiak et al., 1987; McMiken et al., 1983). Whether maximal tolerable current intensity induced maximum torque was addressed by Laughman et al. (1983) and Owens and Malone (1983) in which they monitored the force of the EMS-induced contraction. Laughman et al. (1983) reported an average of 33% MVIC induced by maximal tolerable current intensity while Owens and Malone (1983) reported 39% and 60% MVICs in the two stimulation groups.

The controversy exists in Kots' claim that EMS-induced contraction by maximal tolerable current was able to produce 110% to 130% MVIC. Ferguson et al. (1989) investigated the correlation between the current intensity tolerated and the EMS-induced torque and reported significant correlation coefficients ranging from 0.54 to 0.73 in four out of five different electrode placements. However, Kubiak et al. (1987), Laughman et al. (1983), and Selkowitz (1985) stated no consistent correlation between the current intensity and the resulting muscle torque.

It therefore appears that Kots' (1977) claim held true only individually as he was reporting results with elite athletes. The maximal current intensity tolerated by the 3 out of 12 university students in the stimulation group produced an average %MVIC ranging from 109.5 to 129.2 (Selkowitz,

1985). Delitto et al. (1989) trained an elite weight lifter with maximum tolerable current intensity which produced an average electrically elicited torque of 112% MVIC, ranging from 95% to 126%.

Stimulation Frequency

Stimulation frequency affects the tension developed in normal muscle (Copper & Eccles, 1930; Sugai, Walsley, & Payne, 1975). Sufficient stimulation frequencies cause the summation of muscle twitches in order to produce high tension tetanic contractions (Åstrand & Rodahl, 1986; Urbscheit, 1987). Rate coding (frequency of nerve excitation) was suggested to be important in tension buildup in the muscle (Åstrand & Rodahl, 1986; Robinson, 1989b). Motor units are composed of either type I or type II fibers of which the rate coding of the motor nerves for tetanus contractions are about 20 and 50 Hz respectively (Åstrand & Rodahl, 1986). Åstrand & Rodahl (1986) stated that the higher the rate coding and the larger the number of fibers in a [motor] unit, the greater the force developed by the activated muscle will be.

Studies (Kramer, Lindsay, Magee, Mendryk, & Wall, 1984; De Domenico & Strauss, 1986; Walmsley et al., 1984) indirectly investigated the effect of stimulation frequencies on the magnitude of EMS-induced contraction. These studies included not only the variable of frequency, but also different waveforms, electrical stimulators, and pulse durations. Walmsley et al. (1984) compared the isometric knee extension torques generated by volition and four stimulators, which delivered currents of (a) medium frequencies of 4000 and 4100 Hz modulated at 75 Hz, (b) single

spike wave of 200 μs in duration at 60 Hz, (c) sine wave with carrier frequency of 2200 Hz modulated at 50 Hz, and, (d) balanced, bidirectional wave of 200 μs in duration at 50 Hz, at voluntary, EMS-induced, and superimposed contraction conditions (Table 2). They compared torque productions between (a) and (b), and (c) and (d) in two subexperiments respectively and reported no significant difference between (a) and (b) or (c) and (d) at either EMS-induced or superimposed contraction conditions.

De Domenico and Strauss (1986) compared the isometric knee extension torques generated by seven electrical stimulators at maximal tolerated current intensity. The currents' characteristics were (a) unidirectional twin spike wave of 100 μs in duration at approximately 65 Hz, (b) "interferential" bidirectional symmetrical square wave of 0-50 μs in duration at beat frequencies from 58 to 73 Hz, (c) "interferential" sine wave of 100 μs in duration at beat frequencies from 50 to 80 Hz, (d) bidirectional symmetrical modified square wave of 50 μs in duration at 100 Hz, (e) bidirectional asymmetrical modified square wave of 250 μs in duration at approximately 65 Hz, (f) bidirectional symmetrical modified square wave of 50 μs in duration at approximately 65 Hz, and (g) bidirectional asymmetrical spike of 200 μs in duration at 50 Hz (Table 2). They reported no significant difference in EMS-induced isometric torque among seven currents of different stimulation frequencies.

Kramer et al. (1984) also compared isometric knee extension torque generated by volition and three electrical stimulators at three contraction conditions. The currents' characteristics were (a) bidirectional asymmetrical square wave of 1,000 μs in duration at 100 Hz, (b) bidirectional

Table 2. Summary of Selected Studies Concerning the Effect of Waveform and/or Stimulation Frequency on EMS-induced Torque Production

Waveform[a]	Stimulation Frequency	Pulse Duration	Current Intensity	Design	Result[b]
De Domenico & Strauss (1986)					
(A) U Twin Spike	65 Hz	100 μs	Tolerable	Repeated	No difference among
(B) S B [IF] Square	58-73 Hz	0-50 μs	I_{max}[c]	measures	the seven wavefroms
(C) S B [IF] Sine	50-80 Hz	100 μs			in highest %MVIC
(D) S B Mod Square	100 Hz	50 μs			
(E) A B Mod Square	65 Hz	250 μs			
(F) S B Mod Square	65 Hz	50 μs			
(G) A B Spike	50 Hz	200 μs			
Kramer et al. (1984)					
(A) A B Rectangular	100 Hz	1000 μs	Tolerable	Independent	(A) > (B) > (C)
(B) A B Spike	100 Hz	200 μs	I_{max}	groups	in average torque
(C) U Square	45 Hz	2000 μs			
Walmsley et al. (1984)					
(A) IF Sine	75 Hz	?[d]	Tolerable	Repeated	No difference
(B) Single Spike	60 Hz	200 μs	I_{max}	measures	between (A) & (B)
(C) Interrupted Sine	50 Hz	450 μs			or (C) & (D) in
(D) Balanced B	50 Hz	200 μs			maximum torque
Reisman (1984)					
(A) Interrupted Sine	constant	0.4 ms[e]	Tolerable	Repeated	(A) > (B) & (C) > (B)
(B) A B	at	300 ms	I_{max}	measures	in mean %MVIC
(C) S B	50 Hz	250 ms			
Snyder-Mackler et al. (1989)					
(A) Interrupted Sine	constant	400 μs	Tolerable	Repeated	(A) > (B) & (C) > (B)
(B) IF Sine	at	250 μs	I_{max}	measures	in %MVIC
(C) S B Square	50 Hz	400 μs			

Note. Target muscles in all studies were quadriceps muscles.

[a]U: unidirectional, S: symmetrical, B: bidirectional, A: asymmetrical; Mod: modulated, IF: interferential. [b]Only EMS-induced contraction results were reported in this table. [c]Maximal tolerable current intensity. [d]Not clearly documented. [e]The unit of pulse duration was misprinted in the original paper because the pulse duration was too long to constitute the stimulation frequency.

asymmetrical spike wave of 200 μs in duration at 100 Hz, and (c) unidirectional square wave of 2,000 μs in duration at 45 Hz (Table 2). They reported that the torque generated by the current of 45 Hz was significantly lower than the other two currents at 100 Hz under the EMS-only condition. As well, the torque associated with the spike waveform of 100 Hz was significantly less than the square wave of 100 Hz.

Two studies (Kramer, 1987b; Mohr, Danzl, Akers, & Landry, 1986) directly addressed the effect of frequencies on the magnitude of electrically induced isometric knee extension contraction. They delivered currents of the same characteristics--pulse duration and waveform throughout the studies at various stimulation frequencies. Mohr et al. (1986) delivered the current of twin peak wave of approximately 28 and 27 μs in duration at 50, 80 and 120 Hz to the quadriceps muscles at maximal tolerated current intensity. There was no significant difference in the EMS-induced torque among the three frequencies. Kramer (1987b) stimulated subjects' quadriceps using a balanced asymmetrical bidirectional square wave of 1,000 μs pulse duration at maximal tolerated current intensity. He compared the EMS-induced torques of 20, 50 and 100 Hz at two contraction conditions and with MVIC. The torque of the EMS-only contraction at 20 Hz was significantly lower than those of 50 and 100 Hz. However, there was no difference between the EMS-only contractions at 50 and 100 Hz.

Hultman et al. (1983) compared three techniques for electrical stimulation to the knee extensors. The stimulation techniques were percutaneous via large aluminum foil electrodes or via ordinary ECG-electrodes and intramuscular via platinum-coated wires. By using the

constant current electrical stimulator, they assessed the voltage for evoking a contraction and the magnitude of EMS-induced torques with the variation of frequency and pulse duration. The authors reported that the 20-hertz frequency was able to induce torque up to 70% MVIC by using either of the percutaneous stimulation techniques. If the frequency was increased to 50 Hz, the force produced could reach 100% MVIC.

Sugai et al. (1975) studied the adductor pollicis muscle and found that complete fusion of EMS-induced twitches occurred at 40 and 50 Hz in 80% of their subjects. Frequencies below 40 Hz, however, caused reduced tension because of incomplete fusion of muscle twitches. The functional characteristics of the quadriceps muscle are similar to that of the adductor pollicis muscle when electrically stimulated by currents with similar stimulation frequency and pulse durations (Edwards, Young, Hosking, & Jones, 1977).

Therefore, it appears that frequencies below 50 Hz cause reduced EMS-induced torque of knee extension because of incomplete summation of electrically induced twitches. In addition, frequencies between 50 to 100 Hz seem to be acceptable for augmenting torque production of knee extension.

Waveform

Studies (De Domenico & Strauss, 1986; Kramer et al., 1984; Reisman, 1984; Synder-Mackler, et al., 1989; Strauss & De Domenico, 1986; Walmsley et al., 1984), addressing the effect of waveforms on the magnitude of EMS-induced torques, employed various electrical stimulators to generate currents of different waveforms.

Three studies (De Domenico & Strauss, 1986; Kramer et al., 1984; Walmsley et al., 1984), which have been mentioned in the previous section, also indirectly addressed the effect of waveform on electrical stimulation induced torque production (Table 2). These studies involved the variations of stimulation frequencies, pulse durations and waveforms. De Domenico and Strauss (1986) reported no significant difference in EMS-induced isometric torque among seven currents of different waveforms. Kramer et al. (1984) reported that the bidirectional asymmetrical square wave generated the highest torque among the three waveforms and that of bidirectional asymmetrical spike wave was higher than the unidirectional square wave. Walmsley et al. (1984) did not describe the waveform of the two pairs of currents separately compared in two subexperiments. They reported no significant difference in electrical stimulation induced torques within pairs.

Studies (McNeal & Baker, 1988; Reisman, 1984; Snyder-Mackler et al., 1989) investigated the difference in torque generated by various waveforms with stimulation frequencies kept constant. Reisman (1984) delivered currents of three waveforms--(a) sine wave with carrier frequency of 2500 Hz interrupted every 10 ms for 10 ms, (b) bidirectional asymmetrical wave with pulse duration of 300 ms, and (c) bidirectional symmetrical wave with pulse duration of 250 ms at maximal tolerable current intensity [The present author believes that Reisman misprinted the unit of pulse duration because the pulse duration was too long to constitute the frequency]. The stimulation frequency of the three currents was 50 Hz. He concluded the sinusoidal and bidirectional symmetrical waves generated

significant higher isometric knee extension torque than that of the bidirectional asymmetrical wave (Table 2).

Snyder-Mackler et al. (1989) employed a similar design with three waveforms as follows: (a) sine wave with carrier frequency of 2500 Hz interrupted every 10 ms for 10 ms, (b) "interferential" sine wave with carrier frequencies of 4000 and 4050 Hz, and (c) bidirectional symmetrical square wave with pulse duration of 400 μs. The stimulation frequency was 50 Hz. These authors reported that the EMS-induced torques at maximal tolerable current intensity by the three currents were 61.6, 40.05, and 54.1% MVICs respectively and concluded that the torques induced by the sinusoidal and bidirectional symmetrical square waves were significantly higher than that of the "interferential" sine wave. However, there was no significant difference between torques produced by the sinusoidal and bidirectional symmetrical square waves.

McNeal and Baker (1988) included eight independent variables--joint angle, electrode size, electrode placement, polarity of stimulation, method of stimulation, gender, target muscle and waveform in their multipurpose study which included only ten subjects. The dependent variable, measured as torque of isometric muscle twitch, was induced by a train of 12 pulses, each separated by 2 s at a given set of stimulation parameters. Data analysis was handled in a descriptive way. Stimulation parameters used in investigating the effect of waveform on the isometric twitch was the current with phase duration of 0.3 s at the intensity of 60 mA delivered at 0.5 Hz by bipolar method. They concluded that the bidirectional symmetrical square wave produced a significantly higher torque than the unidirectional square wave

averaging a 20% to 25% increase. This finding was true for both stimulated quadriceps and hamstrings muscles with both sizes of electrodes and over all tested electrode location.

The two waveforms used in Strauss and De Domenico's (1986) study were (a) "interferential" sine wave with basic carrier frequency of 5000 Hz and resulting beat frequency varying from 50 to 80 Hz and (b) unidirectional twin peak with pulse duration of 100 μs and frequency of approximately 65 Hz. They reported no significant difference in EMS-induced isometric torques with the two waveforms in elbow flexion and extension or knee extension at six levels of joint angles.

Stefanovska and Vodovnik (1985) compared the training effect of square and sinusoidal currents with stimulation frequency of 25 Hz by using the 10:50:10 format. The square current was unidirectional with a pulse duration of 300 μs while the sinusoidal current had a carrier frequency of 2500 Hz interrupted every 20 ms for 20 ms. The stimulation current intensity was adjusted to produce 5% of individual averaged MVIC. The quadriceps muscle was stimulated daily for 3 weeks. The average increase in posttest MVIC was 25.3% and 13.2% for square and sinusoidal currents respectively. The foregoing percentages were not the absolute difference between pre and posttest MVIC scores, expressed as the percentage of the pretest score. Instead, they have been mathematically manipulated with regression coefficients. However, the authors provided no further explanation for using this procedure.

Waveform can be described as unidirectional, bidirectional symmetrical, bidirectional asymmetrical balanced, or bidirectional asymmetrical unbalanced. In combination with different shapes of waves, such as rectangular, sawtooth, triangular, twin spike, single spike, or trapezoidal, there are many different waveforms. The studies reviewed on the efficacy of waveforms on torque production covered only a small facet of the issue. The common point shared by the foregoing studies under "Waveform" was that they did not equalize the pulse charge among various waveforms. The difference in pulse charge itself might be an alternate explanation to the discrepancy in torque production capacity of various waveforms. The evidence reviewed was inclined to favor the bidirectional symmetrical rectangular waveform in torque production. However, further studies are warranted concerning this issue.

Perceived Discomfort Associated with EMS

In order to enhance the effectiveness of EMS in muscle strengthening, the current parameter, stimulation parameter, training parameter, and ecological parameter should be monitored in favor of torque production. At the same time, factors that suppress the torque production should be eliminated or minimized. Two possible suppressing factors, which are by no means exclusive, are muscle fatigue (Åstrand & Rodahl, 1986; Stefanovska & Vodovnik, 1985) and perceived discomfort (Currier, 1987). Muscle fatigue, which is especially common in isometric contraction, is beyond the scope of this study and has not be reviewed.

Perceived discomfort, as perceived exertion (Borg, 1974), was defined as a "gestalt" of many feelings and sensations related to the EMS. Currier (1987) stated that a subject's discomfort might be a limiting factor in torque production. As current intensity was increased, the subject's sensory input also increased, which tended to limit the amount of current that could be tolerated. For example, subjects in the studies by Currier and Mann (1983), Halbach and Straus (1980), Kramer (1987b), Owens and Malone (1983), and Walmsley et al. (1984) acknowledged experiencing the pain that limited the amount of current they could tolerate.

Perceived discomfort will provoke reflex inhibition of the stimulated muscle through Renshaw cells and subsequently limits the force producing capacity of the muscle (Åstrand & Rodahl, 1986). Cocontraction of the antagonist is another physiological phenomenon associated with the perceived discomfort caused by EMS (Currier & Mann, 1983; Laughman et al., 1983; Selkowitz, 1985). The effect of volitional antagonist cocontraction affecting electrical induced agonist in strengthening capacity, which has yet to be investigated, is beyond the scope of this study.

Two common sensations associated with EMS are skin discomfort (Currier & Mann, 1984; Kramer, 1987b; Mohr et al., 1986) and muscle soreness (Currier & Mann, 1984; De Domenico & Strauss, 1986; Halbach & Straus, 1980; Soo et al., 1988; Walmsley et al., 1984). Subjects in the studies (Currier and Mann, 1984; De Domenico and Strauss, 1986; Soo et al., 1988) experienced muscle soreness similar to delayed onset muscular soreness (Armstrong, 1984). Muscle soreness occurred after the first or

second EMS session, but subsided within two or three days (De Domenico & Strauss, 1986; Soo et al., 1988).

Subjects in De Domenico and Strauss' (1986) and Walmsley et al.'s (1984) studies noted "cramping" and "tearing" feelings in the muscle. Currier and Mann (1984) administered a four-part modification of the McGill Pain Questionnaire (MPQ) upon termination of five weeks of training to investigate (a) locations of discomfort, (b) word descriptors associated with the training modes, (c) changes of pain with time, and (d) intensity of pain experienced during the training. Subjects in the stimulation group received sine waves with a carrier frequency 2500 Hz interrupted every 10 ms with a stimulation frequency of 50 Hz . The common word descriptors for muscle soreness were "sore", "nagging" and "tight" while "burning" and "throbbing" were used for the pain (Currier & Mann, 1984). Most subjects described the nature of pain as "pins and needles", "buzzing", "throbbing", or "grasping" in Balogun's (1986) study in which he used the identical stimulation protocol as Currier and Mann (1984). Balogun (1986) also noted that the individuals perceived pain at high current intensity differently and that the maximal tolerable intensity was not always associated with the most excruciating experience of pain. However, he provided no further explanation.

Current Characteristics Affecting Perceived Discomfort

Many studies (Currier & Mann, 1983; De Domenico & Strauss, 1986; Halbach & Straus, 1980; Kramer, 1987b; Mohr et al., 1985, 1986; Owens & Malone, 1983; Soo et al., 1988; Walmsley et al., 1984) monitored the perceived discomfort associated with EMS. However, there were few studies measuring the effect of stimulation current characteristics on the perceived discomfort. Some studies (Baker et al., 1988, Baker, Cornell, Flannery, Herman, McNeal, & Tomasu, 1989; Baker, McNeal, Dewart, Shaieb, Thurman, & VanDuzer, 1989; Bowman & Baker, 1985; Gracanin & Trnkoczy, 1975; Vodovnik et al., 1965) addressed the issue based on subjects' preference. Other studies used a measuring instrument -- e.g. MPQ (Currier & Mann, 1984), 5-level ordinal scale (Gracanin & Trnkoczy, 1975), 10-point ratio scale adapted from Borg's Rating of Perceived Exertion Scale (Balogun, 1986), and Visual Analog Scale (VAS) (Delitto & Rose, 1986; Wong, 1986).

Stimulation Frequency

Vodovnik et al. (1965) investigated the pain response to different tetanizing currents by including the variables of waveform, pulse duration and stimulation frequency. They applied bidirectional currents of sine or square waves to the finger extensors using eight stimulation frequencies delivered in decending order ranging from 20 to 3000 Hz. Current intensity was increased until the finger tips were lifted two inches above the table. The painful frequency was identified as that level at which the subject forcefully expressed a feeling of pain or discomfort. They reported that the

majority of subjects felt uncomfortable for both currents at frequencies below 200 Hz.

Gracanin and Trnkoczy (1975) reported a study on optimal parameters causing minimal pain while stimulating the peroneal nerve. The five parameters tested were pulse duration, stimulation frequency, waveform, impedance of stimulator output, and direct current bias. Each subject rated the different parameter combinations on a 5-level ordinal scale--insensible, comfortable, tolerable, unpleasant, and painful. For each set of stimulation parameters, the current intensity was increased until a 5-newton-meter torque was measured at the ankle. The influence of three frequencies was investigated in only five subjects. However, the parameter combination with the frequencies was not clearly documented. Gracanin and Trnkoczy (1975) concluded that there was no significant difference in preference among 20, 50, and 100 Hz.

Kramer (1987b) used a questionnaire to assess the skin discomfort associated with EMS in a study which was to compare the effect of stimulation frequency on isometric knee extension torque. Kramer (1987b) reported that the majority of the subjects indicated skin discomfort at the 20-hertz frequency while no complaints were made regarding the 50-hertz frequency, and only one subject reported the 100-hertz frequency to be uncomfortable. Overall, 68% of the subjects reported that skin discomfort was the major limiting factor of the magnitude of EMS-induced contraction at 20 Hz.

The literature review thus illustrates that stimulation frequency of above 50 Hz was favored by subjects in terms of skin discomfort in EMS.

Waveform

Vodovnik et al. (1965) compared bidirectional sine and square waves in pain response and concluded that there was no essential difference between the bidirectional sine and square waves for frequency equal to or higher than 500 Hz. However, at lower frequencies, the bidirectional square wave was slightly more favorable. They also concluded that no essential difference was noted between unidirectional rectangular and exponential waves.

When studying the effect of waveform on pain response, Gracanin and Trnkoczy (1975) used two waveforms (square & exponential), two pulse durations (0.3 ms & 1 ms), and two types of stimulator output impedance (constant current & constant voltage). The eight parameter combinations were delivered to 10 subjects three times. The order of parameter combinations delivered was different each time. As mentioned in the last section, the subjects rated the degree of pain for each parameter combination on a 5-level ordinal scale. However, Gracanin and Trnkoczy (1975) reported the result in a dichotomized category of preference and no preference. Furthermore, they did not indicate how to dichotomize the 5-level ordinal scale into two categories. Their conclusion was that there was no difference in the sensation when using the rectangular or exponential waves.

Delitto and Rose (1986) compared the relative comfort levels among three waveforms--sinusoidal, sawtooth, and square (Table 3). They delivered currents of identical characteristics, but different waveforms, to subjects' knee extensors at an intensity that induced the torque level to 60% MVIC. The current had a carrier frequency of 2500 Hz interrupted every 10 ms for 10 ms resulting in a stimulation frequency of 50 Hz. Stimulation duration was eight seconds with a five-second surge time. Waveforms were randomly delivered once with a three-minute rest between each waveform. Subjects rated their comfort level on a VAS. In addition, the comfort levels were ranked according to waveforms to determine whether any one waveform was ranked most often with the highest level of comfort. They concluded that no difference was noted in the comfort levels among waveforms, nor did any one waveform produce a more comfortable contraction.

Bowman and Baker (1985) investigated the effects of variations in pulse duration, waveform symmetry, and output impedance of stimulator on comfort during stimulation of knee extensors at an intensity necessary to produce a 27-newton-meter torque. The waveform was asymmetrical or symmetrical bidirectional rectangular waves with balanced charge. The current of either waveform was delivered at 35 Hz with a pulse duration of 300 μs for 1.5 s without any intensity modulation. Subjects rated the pair of the prechosen combination of stimulation parameters as preference or no preference. There were 15- and 45-second rest periods within and between pair comparisons respectively. Comparisons of the same pair of stimuli were repeated a total of 12 times and each subject was tested using the same

Table 3. Summary of Selected Studies Concerning the Effect of Waveform on Comfort

Waveform[a]	Carrier Frequency	Stimulation Frequency	Pulse Duration	Current Intensity	Result
Wong (1986)[b]					
(A) U Twin Spike	N.A.[c]	constant at 50 Hz	40 μs	Tolerable I_{max}[d]	(A) was significantly more comfortable than (B) in an ankle plantar flexors stimulation only
(B) A B [square]	N.A.		300 μs		
Delitto & Rose (1986)[e]					
(A) S B Sine	constant at 2500 Hz	constant at 50 Hz	constant at 400 μs	60% MVIC	No significant difference among three waveforms
(B) S B Sawtooth					
(C) S B Square					

[a]U : unidirectional; A : asymmetrical; B : bidirectional; S : symmetrical. [b]Target muscles of the study were knee extensors & ankle plantar flexors. [c]Not Applicable. [d]Maximal tolerable current intensity. [e]Target muscle of the study was knee extensors.

random order. They reported that 86% of 63 responses and 6 out of 8 subjects favored the symmetrical waveform when the current was regulated. When the voltage was regulated, 68% of 79 responses and 5 out of 10 subjects favored the same symmetrical waveform.

Baker et al. (1988) administered three sets of three waveforms to subjects when comparing the effects of waveform on comfort on three occasions (Table 4). The six waveforms included (a) asymmetric balanced bidirectional square wave with pulse duration of 300 μs, (b) symmetric bidirectional square wave with phase duration of 300 μs [It is not certain whether the authors used "phase" and "pulse" interchangeably], (c) unidirectional paired spike wave with single spike phase duration of 5 μs, (d) modulated [interferential] sine wave with a carrier frequency of 4000 Hz, (e) medium frequency of 2500 Hz sine wave enveloped into 10-millisecond packages, and (f) medium frequency of 2500 Hz with square waves enveloped into 10-millisecond packages. The first set consisted of waves (a), (b), and (c) which were delivered at 50 Hz to the wrist flexors and extensors. The other two sets, which were delivered to the knee extensors, consisted of waves (b), (c), and (d); and (b), (e), and (f) respectively. In the first phase of lower extremity stimulation, the frequencies of (b), (c), and (d) were 32, 35, and 100 Hz respectively. In the second phase, the frequency of the three compared waveforms was 50 Hz. The current intensity of each waveform was increased until the stimulated muscle generated the predetermined torque. For each occasion, subjects were given stimulus pairs randomly with each stimulus lasting for 1.5 s. There were 15- and 60-second rest periods within and between pair comparisons respectively.

Table 4. Summary of Baker et al.'s (1988) Study Concerning the Effect of Waveform on Comfort

Waveform[a]	Carrier Frequency	Stimulation Frequency	Pulse Duration[b]	Current Intensity	Result[c]
First Phase					
(B) S B Square	N.A.[d]	32 Hz	300 µs	To generate	90%, vs (C); 83%, vs (D)
(C) U Paired Spike	N.A.	35 Hz	5 µs	20 ft-lb	4%, vs (B); 18%, vs (D)
(D) Mod [IF] Sine	4000 Hz	100 Hz	?[e]	isometric knee	13%, vs (B); 70%, vs (C)
Second Phase				extension	
(B) S B Square	N.A.	50 Hz	300 µs	torque	66%, vs (E); 71% vs (F)
(E) Mod MF Sine	2500 Hz	50 Hz	?		34%, vs (B); 51%, vs (F)
(F) Mod MF Square	2500 Hz	50 Hz	?		18%, vs (B); 30% vs (E)

Note. Only lower extremity results were reported in this table.

[a]S : symmetrical; B : bidirectional; U : unidirectional; Mod : modulated; IF : interferential; MF : medium frequency. [b]It was not certain whether "phase" and "pulse" were used interchangeably in the study. [c]Percentage of preference response of the waveform in comparison with other waveforms. [d]Not Applicable. [e]Not clearly documented.

Subjects rated the pair of waveforms within the set as preference, no preference, or nonpreference. Comparisons of each pair of stimuli were repeated at least 10 times. They concluded that the asymmetric balanced bidirectional square wave was perceived as comfortable in wrist stimulation. Furthermore, subjects preferred the square waveforms over the paired spike unidirectional waveform. In the quadriceps muscle stimulation, symmetric bidirectional square waves were perceived as more comfortable than the other four waveforms.

Wong (1986) compared the 40-microsecond unidirectional twin peak and 300-microsecond asymmetric balanced bidirectional [rectangular] waves on perceived discomfort (Table 3). Currents were randomly delivered to either knee extensors or ankle plantar flexors at maximal tolerable level for six minutes with a 10-millisecond on and off cycle. However, other current characteristics remained constant. Subjects rated the perceived discomfort level of the stimulation on a VAS and the two waveforms as preference or no preference. Wong (1986) concluded that the unidirectional twin-peak wave was significantly more comfortable than the asymmetrical balanced bidirectional [rectangular] wave in the ankle plantar flexors only.

Conclusions from the studies reviewed were not unanimous. However, the evidence tends to agree that symmetric and bidirectional square waves were favored in terms of comfort.

Effect of Pulse Duration on Torque Production and Perceived Discomfort

Vodovnik et al. (1965) investigated the pain response of pulse duration by stimulating subjects' finger extensors with an unidirectional rectangular wave of 12 pulse durations ranging from 100 to 20,000 μs. They suggested that pulse durations below 300 μs were more comfortable.

Gracanin and Trnkoczy (1975) only compared the pain response on two pulse durations--300 and 1,000 μs. They concluded that a pulse duration of 300 μs was more comfortable than 1,000 μs.

The preference between 50- and 300-microsecond pulse [phase] durations was investigated in Bowman and Baker's (1985) study. They reported that the preference of 300 μs was overwhelming. With a constant current stimulator, 9 out of 11 and 10 out of 11 subjects preferred 300 μs in unidirectional and symmetrical bidirectional rectangular wave stimulations respectively. With a constant voltage stimulator, all, and 9 out of 11 subjects preferred 300 μs in unidirectional and symmetrical bidirectional rectangular wave stimulations respectively. Overall, 89% out of 220 responses favored 300 μs.

Without giving details on the method used, Hultman et al. (1983) reported that there was a marked increase in the tension evoked in the knee extensors when the pulse duration was increased from 200 to 1,000 μs (Figure 6). Figure 6 illustrates that a plateau is reached with a duration of 1,000 μs. Two subjects experienced centripetal sensation without further

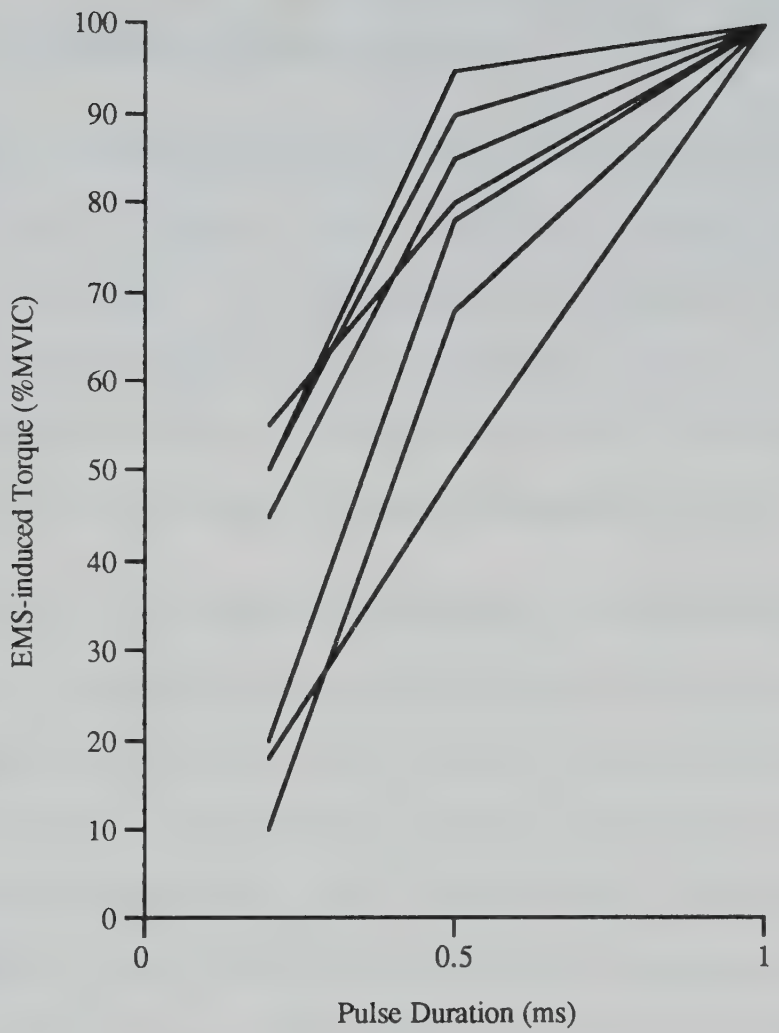

Figure 6. The Relationship between EMS-induced Torque (in %MVIC) and Pulse Duration (Adapted from Hultman et al. , 1983).

(Note: Each line represented a subject)

appreciable increase of tension when the duration was prolonged from 1,000 to 10,000 μs. They suggested that a pulse duration of 500 to 1,000 μs was optimal because a low stimulation voltage could be used to produce maximum force with minimum discomfort.

Alon et al. (1983) studied the effects and interactions of pulse duration and pulse charge on sensory, motor, painful, and maximal tolerable painful responses on six males. An unidirectional square wave at 20 Hz with pulse duration varied at logarithmic intervals from 5 to 1,000 μs was used to stimulate the elbow extensors. They found that the current with pulse duration of 100 μs produced the greatest non-painful torque.

Therefore, it appears that currents with a pulse duration from 100 to 1,000 μs were comfortable and suitable for motor stimulation. However, the five studies quoted were mainly descriptive as no inferential statistical analysis was made. Gracanin and Trnkoczy (1975) and Vodovnik et al. (1965), using an ordinal pain scale, viewed the pain response on different pulse durations instead of optimal pulse duration to produce maximal torque with minimal discomfort. Vodovnik et al. (1965) indicated that it would be more desirable to use more precise methods for measuring pain. Alon et al. (1983) reported that the quality of pain perception was distinctly different between the very short and very long pulses. The former was a sharp, pin prick while the latter was a burning pain sensation. The use of the word "pain" might be misleading and instead "discomfort" might be more appropriate. Alon and coworkers (1983) interpreted the optimal pulse duration to generate maximum torque. However, they did not standardize the current intensity delivered. One may argue then that the variation of

torque production at different pulse durations was merely due to different current intensities delivered. Alon et al. (1983) included the charge-torque ratio (CTR) to find the optimal pulse duration. The lower the CTR, the more optimal the pulse duration. However, Alon et al. (1983) and Hultman et al. (1983) did not measure the pain or discomfort sensation, nor did they relate the pain sensation to pulse duration. In interpreting the result of Hultman et al.'s (1983) study, cautions should be taken because their subjects were locally and superficially anesthetized. Hence, Hultman et al.'s (1983) findings may not be fully generalizable to other populations.

Summary

EMS is effective in strengthening normal muscle. In order to improve its effectiveness, optimal current characteristics which induce maximal muscle torque production with minimal perceived discomfort must be investigated. Based on the literature reviewed, it was believed that bidirectional symmetrical square waves and stimulation frequencies of 50 to 100 Hz were favored in stimulating normal muscle. Furthermore, the wide range of the suggested "optimal" pulse durations need to be refined.

CHAPTER THREE

MATERIALS AND METHODS

Research Design

The study was a single factor (pulse durations) design with repeated measures over pulse durations. There were two dependent variables, namely EMS-induced isometric knee extension torque and perceived discomfort. The independent variable (pulse duration) had five levels--200, 400, 600, 800, and 1,000 μs. Only one trial on each pulse duration was conducted on each subject as the investigation of the variance of dependent variables among trials was beyond the scope of the study.

The study was originally designed to eliminate the extraneous variable of different current intensities at different pulse durations by using a constant current stimulator. However, the current output of the stimulator was found to vary concurrently with pulse durations in the calibrations of the stimulator (see p. 73 for the calibration result). The effect of different current intensities among pulse durations on the two dependent variables was neutralized by standardizing the two dependent variables with the corresponding current intensities (see p. 71 under 'Treatment of Data' for details). Other extraneous variables, such as stimulation parameters, electrode parameters, and ecological parameters, were set constant throughout the study.

All volunteers attended two sessions--a familiarization session, and a testing session. To minimize any effect of delayed onset muscular soreness from the measurement trials of MVIC in the familiarization session, the two sessions were at least one week apart. In addition, a 2-minute rest was provided between each electrically induced or volitional contraction in order to reduce the threat of muscle fatigue following the first contraction. Sahlin (1986) indicated that the knee extension strength after a fatiguing isometric contraction recovered to 80% MVIC in 30 s and 100% after 4 min. Mundale (1970) cited the result of Hill, Long and Lupton's (1924) work that the local recovery within the muscle from the fatiguing effect of exercise was considered almost complete within 2 or 3 min. Trossman and Li (1989) reported a significantly less difference in hand grip strength between two trials with a 2-minute intertrial rest. Furthermore, the duty cycle of the stimulation current used in the study was 1:10 which was lower than that of Packman-Braun's (1988) study in which he recommended a duty cycle of 1:5 appropriate to minimize muscle fatigue over time. It was felt that, based on this information, it was justified to have the rest period of 2 min between each electrically induced or volitional contraction.

The order of application of the five pulse durations was randomized to each subject. Subjects were blinded from all measurement results and adjustments of the pulse durations.

Subjects

Twenty-five male physical therapy students participated in the study with the following inclusion criteria: (a) no known neurological or orthopedic dysfunctions involving the stimulated lower extremity, (b) no known chronic systemic or dermatologic disease, (c) no expressed fear of or hypersensitivity to EMS, and (d) the ability to complete maximal EMS-induced contractions at all pulse durations. Subjects were excluded from the study if they were able to tolerate a greater current intensity than the electrical stimulator could provide. This procedure prevented the ceiling effect posed by the "insufficient" current output capacity of the stimulator and minimize the subsequent type II error.

Subjects were advised to refrain from vigorous exercise for two hours before testing to avoid pretest muscle fatigue (Wong, 1986) and all subjects signed an informed consent form (Appendix A) before participation.

Apparatus

Measurement Instrument

Dynamometer.

Isometric knee extension torque was measured with a KIN/COM™ isokinetic dynamometer[1]. Angular velocity of the dynamometer was set at 0°/s . The dynamometer was calibrated according to the manufacturer's

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[1] Med•Ex Diagnostics, Inc., 1760 Kingsway Ave., Port Coquitlam, BC V3C 1S5.

instruction (Appendix B) at the beginning of each testing day. The torque value was recorded with a computer which had a rate of data sampling of 100/s. Farrel and Richards (1986), and Tredinnick and Duncan (1988) have documented that the KIN/COM™ dynamometer was valid and reliable in torque measurement. The specifications of the dynamometer are listed in the Appendix C.

Visual Analog Scale.

The perceived discomfort associated with EMS was assessed with a Visual Analog Scale (VAS), a 10-centimeter horizontal line with distinct 1-centimeter demarcations at each end (Figure 7). The left end represented "no discomfort at all" and the right end represented "the worst discomfort imaginable". The reliability and validity of VAS for assessing the subjective perception of pain intensity has been well documented (Ohnhaus & Alder, 1975; Price, McGrath, Rafii, & Buckingham, 1983; Revill, Robinson, Rosen, & Hogg, 1976). Price et al. (1983) validated the use of ratio-level comparisons with VAS.

Oscilloscope.

An oscilloscope[2] was used to assess the electrical stimulator on stimulation characteristics--stimulation frequency, waveform and pulse duration against a 1,000-ohm resistor.

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2 Digital storage oscilloscope Model VC-6050, Hitachi Denshi, Ltd., 65 Melford Drive, Scarborough, Ontario M1B 2G0.

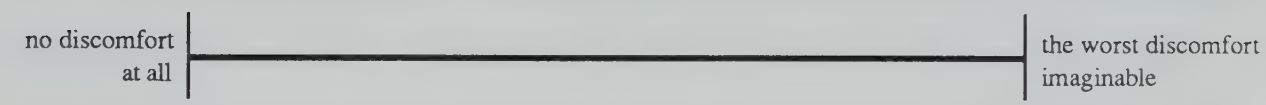

Figure 7. Visual Analog Scale for Perceived Discomfort.

Multimeter.

The skin impedance of all subjects was monitored with a multimeter[3]. The accuracy and constancy of the current output of the electrical stimulator was examined against four resistors (1.0, 2.2, 3.9, 4.4 KΩ) and human skin with another multimeter[4].

Electrical Stimulator

The paramount criterion for choosing an appropriate electrical stimulator for the study was that the stimulator had to generate constant current. By using a constant current stimulator, the pulse charge at a set current intensity was not subject to vary with different skin impedance because this was the property of a constant current stimulator, thereby permitting the researcher to use the same regression equation to predict the actual current output from the stimulator for different subjects at a pulse duration. For the second criterion, the stimulator had to be able to generate bidirectional symmetrical rectangular waves at 50 Hz which has been proven effective in torque production (Hultman et al., 1983; Kramer, 1987b; Mohr et al., 1986) and less associated perceived discomfort (Kramer, 1987b). It was preferable that the stimulator had features of duty cycle and surge controls.

The battery-powered UltraStim®[5] (Appendix D) met all the foregoing criteria and had been chosen for the study. However, there was an inter-pulse [-phase] interval separating the two pulses [phases] (Figure 8). To

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3 Fluke 8050A Digital multimeter, John Fluke MIG Co. Inc., Everett, Washington.
4 Fluke 21 multimeter, John Fluke MIG Co. Inc., Everett, Washington.
5 Model 650-01, Neuromedics, Inc., 802 West Brazos Park, Clute, TX 77531.

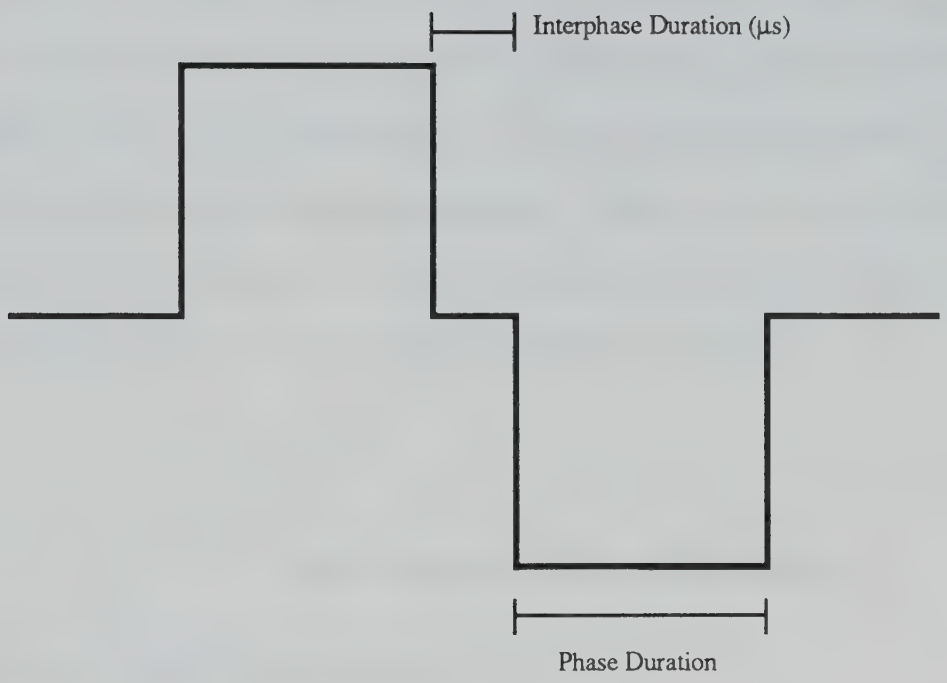

Figure 8. The Waveform of the Stimulation Current of the UltraStim® Stimulator.

date, the effect of inter-pulse [-phase] interval on torque production and perceived discomfort has not been clearly documented. In the literature reviewed, only Bowman and Baker (1985) mentioned that the bidirectional symmetrical square wave used in their study was incorporated with a 20-microsecond interphase interval. Bowman and Baker (1985) cited Van den Honert and Mortimer's (1979) work in which they indicated that the interphase interval of a bidirectional waveform resulted in lower current intensity necessary for muscle excitation. Interphase interval of 40 μs from the UltraStim® was found to be the closest value to that of Bowman and Baker (1985) and had been used throughout the study.

Calibration of the Stimulator

Stimulation Current Characteristics

The accuracies of waveform, frequency and pulse durations of the stimulation current were examined against a 1,000-ohm resistor with an oscilloscope. The output of the oscilloscope was recorded on a Polaroid film (Type 667).

Accuracy and Constancy of Current Output

Against 1,000-; 2,200-; 3,900-; and 4,400-ohm resistors.

The accuracy and constancy (i.e. constant current output irrespective of variations of pulse durations and external resistances) of current output of the stimulator were initially examined against the four resistors with a

multimeter. Resistors higher than 5KΩ could not be used because the stimulator had a built-in safety function in which the stimulation would automatically shut off if the external resistance was higher than 5KΩ. The multimeter read the current output of the stimulator in root-mean-square (RMS) value.

Against Human Skin.

The current output of the stimulator was reexamined against human skin because the constancy of the current output of the stimulator was not established in the first calibration. Two separate subjects were involved in this process. The subject positioning and electrode placement were identical with the formal testing session. The multimeter was connected in series with the electrodes and the stimulator. The stimulation current was maintained until a steady reading was reached from the multimeter. The rest period between stimulations was not controlled.

The calibration range against resistors was 10 to 95 mA or against human skin was to the subject's tolerance at the five different pulse durations. The increment of the stimulation current was 5 mA. The application of current was from low to high and the variation of pulse durations was from high to low.

Procedures

Subjects were advised to wear shorts when attending the familiarization and testing sessions in order to (1) avoid constraint to electrical stimulation and muscle contraction and (2) enable the investigator to observe and monitor muscle contraction.

Familiarization Session

Each subject, who participated in a familiarization session, was informed of the purpose, procedure, and possible risks of the study. Subjects experienced the electrical stimulation contractions at each of the five pulse durations and the MVIC was measured for each one. The purpose of the session was primarily to minimize any learning effect associated with the testing procedure. A familiarization session was believed sufficient because all subjects have had similar stimulation experience from electrotherapy classes as part of their physical therapy program. In addition, the consent form was signed and demographic data--age, height, and weight were collected. Age at last birthday was reported by subjects. Weight (Kg) and height (m) were measured by standard weight scale.

MVIC Measurement.

Prior to experiencing electrical stimulation, the subject's MVIC was measured. The subject's testing position was described under "Testing Session". First, two warm-ups of submaximal isometric knee extension of the same duration as that of the MVIC test (i.e. 12 s each) were practised. All subjects were verbally encouraged at the onset of each formal MVIC test

to give a maximal contraction and were instructed to extend the knee as forcefully as possible and hold for 12 s, which was also identical to the duration of an EMS-induced contraction. Three trials of MVIC were performed to facilitate subjects to achieve maximum effort. The peak torque between the 2nd and 12th second of contraction was used to determine MVIC. The torque values in the first two seconds were not considered as these values might have contaminated with torque overshoots. The highest peak torque among the three trials of MVIC was then used for analysis. There was a 2-minute rest between contractions which had been commonly adopted in Cox, Mendryk, Kramer, & Hunka's (1986), Kubiak et al.'s (1987), and Snyder-Mackler et al.'s (1989) studies.

Familiarization.

With the electrode placement, described under "Testing Session", and pulse duration set at 1,000 μs, the current intensity was increased by the investigator to the maximal tolerable level. Other stimulation parameters were set identical to the testing stimulation. During the familiarization of electrical current, subjects were provided with a remote switch to allow them to activate and terminate stimulation whenever necessary for safety reasons. The maximal tolerable current intensity at 1,000 μs of each subject was recorded as a guideline for determining the subject's maximal tolerable current intensity in the testing session.

Testing Session

The test was at least one week after the familiarization session.

Subject Positioning (Plate 1).

All subjects were tested on the right leg. They were seated in the testing bench with the tested knee positioned at 30° from active full extension. The backrest of the bench was reclined from the seat at angle of 110°. According to Currier (1977), an angle of 110° between the backrest and the seat augmented the production of the isometric knee extension torque. The rotational axis of the dynamometer was aligned with the lateral epicondyle of the right femur to improve reliability of torque measurement. The lever arm pad, against which the lower leg pushed, was placed just above the malleoli so that full range of ankle dorsiflexion was not hindered. The backrest was positioned so that the back of each subject's knee just touched the leading edge of the padded seat. Body stabilization was provided by a back support and a lap seatbelt. Each subject was asked to hang both arms loosely by the side throughout the test.

Stimulation Preparation.

The format of the electrical stimulus was set as described in Table 5. The proximal electrode[6] (7.6 cm x 15.2 cm) was placed over the femoral nerve in the femoral triangle while the distal electrode (7.6 cm x 15.2 cm) was placed transversely across the thigh approximately 2 cm above the base of the patella. The skin, on which the electrodes were placed, was cleaned

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6 Empi, Inc., 1275 Grey Fox Road, St. Paul, Minnesota 55112.

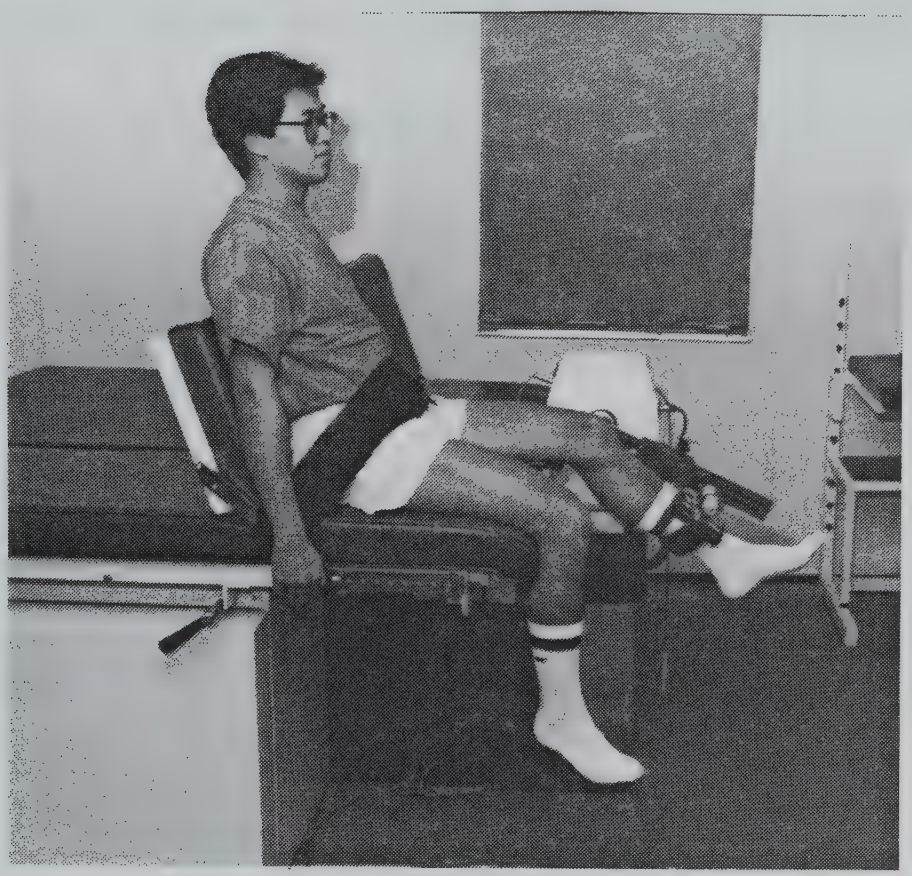

Plate 1. Subject Positioning.

Table 5. Characteristics of Stimulation Current of the Ultrastim® Stimulator

Stimulation Current Characteristics	
Waveform	Bidirectional symmetrical square wave
Stimulation Frequency	50 Hz
Current On & Off Cycle	12 s on, 120 s off
Ramp Up[a]	2 s
Pulse Duration	200, 400, 600, 800, 1,000 μs

[a] length of time for current to rise gradually to preset intensity at the beginning of each current on cycle.

immediately prior to applying the electrodes with Hollister™ universal remover wipe[7] and warm water in order to lower skin impedance. Conductive gel[8] was used as a coupling medium because of the low cost of the gel. The electrodes were fastened in place with prewrap and a four-inch tensor bandage. Once the electrodes had been applied, the subject was properly seated on the bench and provided with a remote switch for activation and termination of stimulation. Prior to the stimulation, the skin impedance was directly measured with a multimeter by attaching the probes of the multimeter to the stimulation electrodes by the investigator.

Stimulation Procedure.

During the EMS-induced contractions, subjects were advised to allow the electrical stimulator to produce the muscular contraction, and not attempt at any voluntary contraction of the quadriceps muscles. Furthermore, they were requested to allow the knee flexors to relax completely.

Prior to the formal stimulation, the maximal tolerable current intensity was determined with pulse duration set at 1,000 μs. The subjects were instructed as follows:

> "The intensity will be increased slowly until you request that it be stopped. I would like you to allow the intensity to be increased until you reach the level you consider to be your "maximal" tolerance. The sensation should be strong but bearable."

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[7] Hollister Limited, 322 Consumers Road, Willowdale, Ontario M2J 1P8.
[8] Aquasonic gel, Aquasonic, Parker Laboraties, Inc., Orange, NJ 07050.

The term "maximal" referred to a subject's ability to complete as strong as an electrically induced muscular contraction using as much electrical current as could be tolerated. Under no circumstances, were the subjects encouraged to accept or reject more current than they requested. The maximal tolerable current intensity was recorded directly from the output meter of the stimulator. The "maximal" tolerable current intensity was delivered once more at 1,000 μs after a 2-minute rest. This maximal tolerable current intensity was considered final if the subject expressed that he was unable to take more current. Otherwise, the current was increased again and the procedure was repeated until the same current intensity was indicated twice as maximal tolerable intensity. The output meter reading of this intensity was used at all pulse durations in the study.

In the formal testing, the current intensity was set to the predetermined level and increased by the investigator. The subject had complete control of when to activate the stimulation by pressing the remote switch. Two seconds were provided to surge the current intensity to the predetermined level and then maintained for another 10 s, all for a total time of 12 s for each contraction. A 2-minute rest was provided between contractions.

Immediately after each contraction, subjects were shown a VAS (Figure 7) and given the following instructions:

> "This line represents a complete dimension of discomfort. The far left-hand side of this line represents 'no discomfort at all', the far right-hand side of this line represents 'the worst discomfort imaginable'. Between the left side and right side of the lines, scores increase from left to right

on discomfort. For example, if you mark to the left of the scale, it would mean that you perceive less discomfort than if you marked more towards the right of the scale. Consider the discomfort you felt from this contraction. Place a mark at the point on the line that you believe represents the amount of discomfort you felt during this contraction."

The subjects then marked the scale without seeing their previous scale marking. There was one contraction on each pulse duration for a total of five contractions.

Measurement

MVIC and EMS-induced Isometric Contraction of Knee Extension

The operational definition of the torques generated by MVIC and EMS-induced isometric contraction of knee extension was the peak value of the recorded torque between the 2nd and 12th second. The torques were gravity corrected according to manufacturer's instruction (Med·Ex Diagnostics, Inc.). The SI unit of torque is Newton-meter (Nm).

Perceived Discomfort

Perceived discomfort associated with EMS was measured with a VAS (Figure 7). The perceived discomfort score was calculated by measuring the distance, in centimeters, from the left margin (zero point) of the VAS to the

subject's marking (subjective perception of discomfort intensity) using a standard metric ruler.

Current Intensity

The current intensity was first recorded from the output meter of the stimulator. This value was later adjusted to RMS value with the regression equations for the corresponding pulse durations (see p. 71 for explanation and justification).

Treatment of Data

Data from Calibrations of the Stimulator

The accuracy and constancy of current output of the stimulator were visualized by plotting the RMS reading of the multimeter against the output meter reading of the stimulator for all pulse durations.

Data from the calibration involving human skin were used to calculate regression equations which were subsequently employed to transform the inaccurate output meter reading of the stimulator into the comparable (among pulse durations) adjusted current intensity in RMS value.

Data from Familiarization Session

Descriptive statistics were used to analyze the demographic data and MVICs.

Data from Testing Session

Stimulation Current Intensity.

The stimulation current intensity from the output meter of the stimulator was transformed into RMS value with a corresponding regression equation (p. 79) generated from the calibration of the stimulator against human skin. The RMS value was later used to standardize the two dependent variables among pulse durations. Descriptive statistics were reported on the adjusted stimulation current intensity.

EMS-induced Isometric Knee Extension Torque and VAS Score.

Since the stimulation current intensity and pulse duration varied concurrently in the study, the two dependent variables were first standardized with the corresponding stimulation current intensity (in RMS value) to neutralize the effect of different current intensities on the two dependent variables before inferential statistics were preformed. For example, standardized EMS-induced isometric knee extension torque (Nm/mA) or VAS score ($x10^{-1}$ cm/mA) at 200 μs =

$$\frac{\text{EMS-induced isometric knee extension torque / VAS score at 200 } \mu s}{\text{Adjusted stimulation current intensity at 200 } \mu s}$$

The significantly and linearly ($R^2 = .99$) correlated ($r = .99$, $p < .05$) relationship between the actual current output intensity and the output meter reading of the stimulator enabled the researcher to predict the actual current intensities to subjects with regression equations. Using the same regression equation for all subjects at a set pulse duration to predict the actual current

output of the stimulator was legitimate because the stimulator generated constant current against human skins of different impedance (i.e. different subjects received the same intensity of actual current output of the stimulator at a set output meter reading).

One-way analysis of variance (ANOVA) with repeated measures was used to test the first and second hypotheses. The Tukey test was used for post-hoc multiple comparisons of means.

EMS-induced Isometric Knee Extension Torque and Stimulation Current Intensity.

The Pearson Product-Moment correlation procedure was used to test the relationship between the EMS-induced isometric knee extension torque and stimulation current intensity (i.e. the third hypothesis).

Skin Impedance.

Descriptive statistics were used to analyze subject's skin impedance.

The Statistical Package for the Social Sciences (SPSSx) program was used for all data analysis. The .05 level of probability was adopted as the level of statistical significance.

CHAPTER FOUR

RESULTS

Calibrations of the Stimulator

Stimulation Current Characteristics

The waveform, stimulation frequency and pulse durations were in line with the designated values (Plate 2).

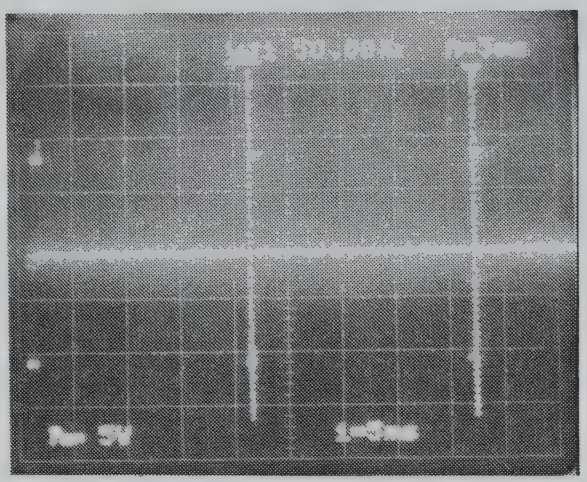
Accuracy of Current Output Reading of the Stimulator

As illustrated in Figure 9, a set current output reading of the stimulator did not equal to the measured RMS values at any pulse duration. Hence, the current output reading of the stimulator was inaccurate.

Constancy of Current Output of the Stimulator

Among Pulse Durations.

Figure 9 also illustrates that at a set current output reading of the stimulator, the RMS value varied with pulse durations. The longer the pulse duration, the higher the measured RMS values were on a current output meter reading. In other words, the stimulator did not generate constant current among pulse durations even though the current output reading of the stimulator was kept constant among pulse durations.



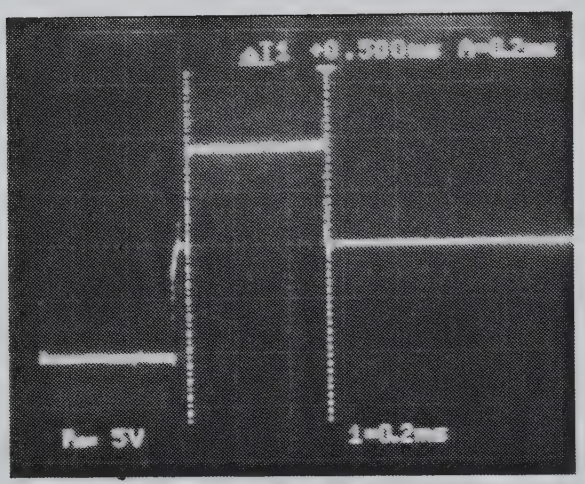


Plate 2. Stimulation Current Characteristics.
(Top : Stimulation Frequency ; Bottom : Phase Duration and Waveform)

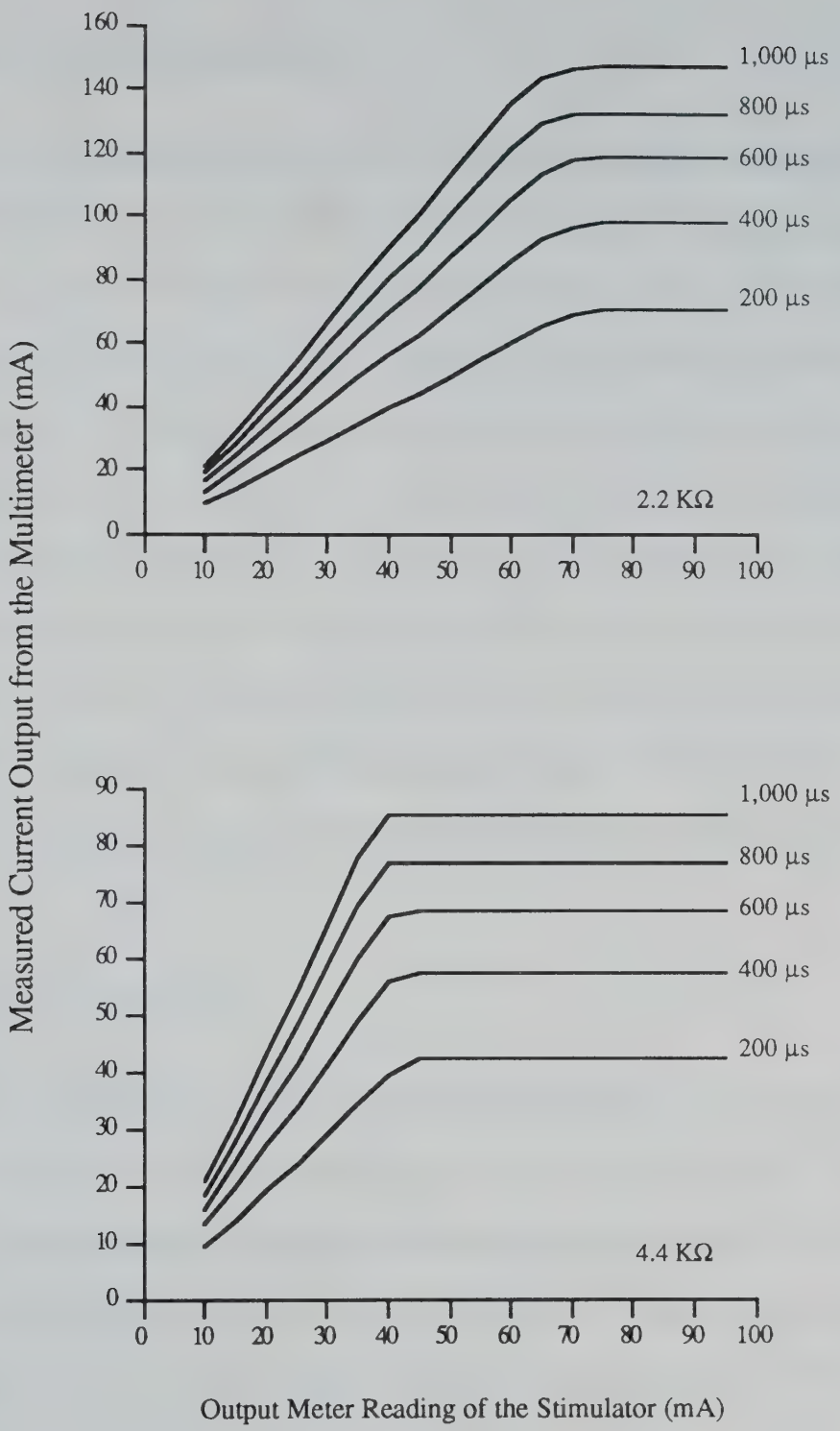


Figure 9. Accuracy and Constancy of Current Output of the Stimulator among Pulse Durations.

Against External Resistors.

With the pulse duration kept constant, the stimulator generated constant current intensity irrespective of variation of external resistance only within a range of the current output of the stimulator (Figure 10). If the stimulation current passed a critical level, the output current remained unchanged regardless of increasing the output meter reading of the stimulator. Beyond the critical level, the stimulator no longer generated constant current against different external resistances. The critical level at which the stimulator stopped generating constant current depended on the magnitude of external resistance (Figure 10). The higher the external resistance, the earlier the critical level appeared in the output current range. However, this critical level was identical among pulse durations at a set external resistance (Figure 9).

Against Human Skin.

Figure 11 illustrates that the stimulator generated constant current to two subjects of different skin impedances at a fixed pulse duration. The actual output current intensity of longer pulse duration increased more than that of shorter pulse duration from the same increment of output meter adjustment of the stimulator. The regression equation for each pulse duration is listed in Table 6.

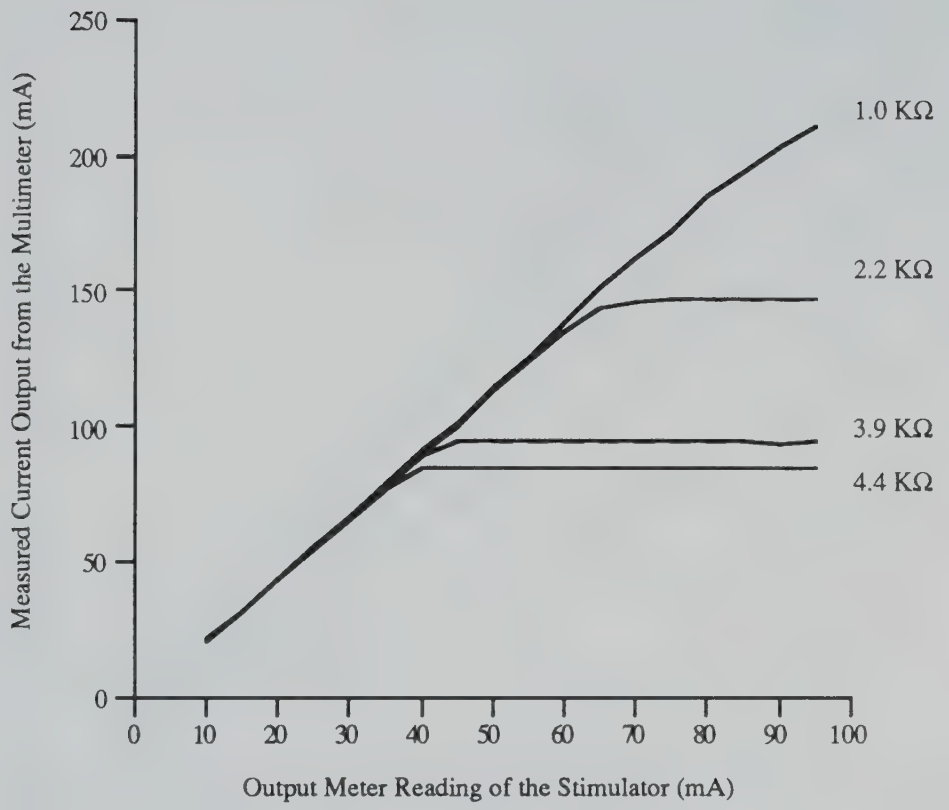


Figure 10. Constancy of Current Output of the Stimulator against Different Resistances at 1,000 μs.

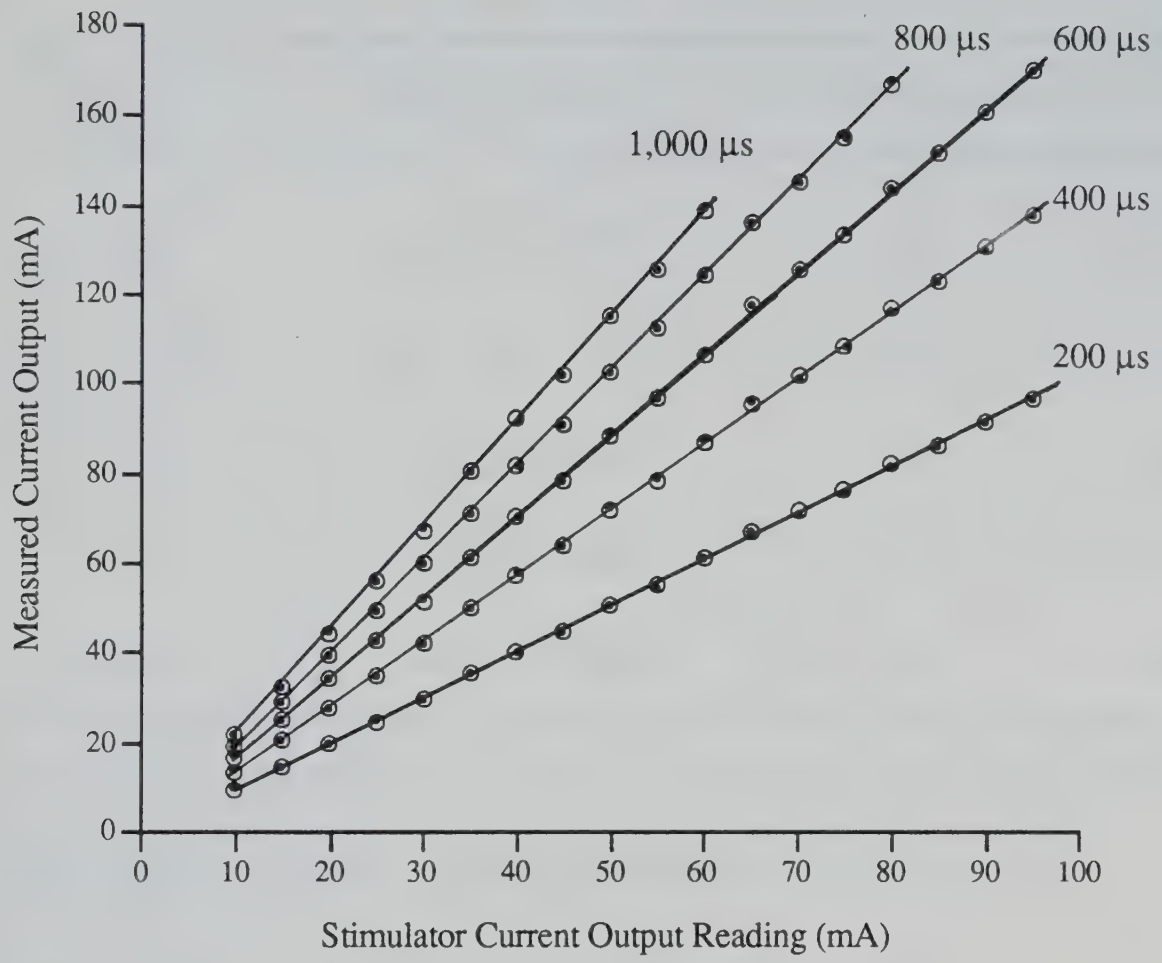


Figure 11. Constancy of Current Output of the Stimulator Against Different Skin Impedances.

(Solid dots : Subject A, Open dots : Subject B)

Table 6. Equations for Transformation of Current Meter Reading of the Stimulator into Comparable Adjusted Current Intensity (RMS Value)

Pulse Duration (μs)	Regression Equation[a]	Correlation Coefficient[b]	R^2
200	y = -1.10 + 1.023x	.99	.99
400	y = -1.87 + 1.467x	.99	.99
600	y = -2.46 + 1.810x	.99	.99
800	y = -2.79 + 2.099x	.99	.99
1,000	y = -2.94 + 2.351x	.99	.99

[a] x = output meter reading of the stimulator, y = comparable adjusted current intensity.

[b] all correlation coefficients are statistically significant ($p < .05$).

Familiarization Session

Subjects

The demographic data of subjects is listed in Table 7. No subject was able to tolerate the maximum current output of the stimulator, therefore all subjects were included in the study.

MVICs

The mean, standard deviation and range of MVICs were 155.16, 33.69, and 90.5 - 216.6 Nm respectively.

Testing Session

The random order of application of pulse duration to each subjects is listed in Appendix E. The bias in the application order of pulse duration was not apparent (Table 8). The mean, standard deviation and range of the adjusted stimulation current intensity at 1,000 μs (i.e. maximum tolerable current intensity) were 128.84, 29.73, and 86.41 - 185.17 mA respectively.

EMS-induced Isometric Knee Extension Torque

The means, standard deviations and ranges of EMS-induced isometric knee extension torques at different pulse durations are listed in Appendix F. The range of EMS-induced torque in %MVIC was 1.74 - 99.62 % regardless of different pulse durations.

Table 7. Demographic Data of Subjects

	Mean	Standard Deviation	Range
Age	24.36	3.59	19 - 32
Weight (Kg)	76.59	9.12	56.0 - 89.80
Height (m)	1.78	0.07	1.67 - 1.95

Table 8. The Application Order of Pulse Durations

	Order of Application				
Pulse Duration (μs)	1st	2nd	3rd	4th	5th
200	6	5	6	4	4
400	5	8	1	8	3
600	6	4	8	5	2
800	5	4	5	2	9
1,000	3	4	5	6	7

Note. Numbers were frequencies of appearance

There were 10 of 150 data missing because the EMS-induced contractions were not sufficient to trigger the dynamometer to register the torques. Among the missing data, four of each were found at 200 and 400 μs, and one each at 600 and 1,000 μs. The missing data were confined in seven cases in which no apparent trend was noticed. Hence, the seven cases were excluded from further analysis.

The first hypothesis was tested with an one-way ANOVA with repeated measures of which the result (Table 9) showed that there was significant difference on EMS-induced torque among the five pulse durations. Therefore, the first hypothesis was rejected. The post-hoc Tukey test (Table 10) revealed that the means of 200 and 400 μs were significantly smaller than that of 600, 800 and 1,000 μs. The mean of 400 μs was significantly greater than that of 200 μs.

VAS Score

The means, standard deviations and ranges of VAS scores at the five pulse durations are listed in Appendix F. The result of one-way ANOVA on VAS scores (Table 9) confirmed that there was a significant difference on VAS scores among the five pulse durations, thereby rejecting the second hypothesis. The post-hoc Tukey test (Table 10) showed that the mean of 200 μs was significantly smaller than that of 400, 600, 800 and 1,000 μs, and the mean of 400 μs was significantly smaller than that of 800 and 1,000 μs.

Table 9. Results of One-way Anova with Repeated Measures (over Pulse Durations) on EMS-induced Isometric Knee Extension Torques (Nm/mA) and VAS Scores ($x10^{-1}$ cm/mA)

Source	*SS*	*df*	*MS*	*F*
EMS-induced Isometric Knee Extension Torques[a]				
Between Subjects	3.33	17	0.196	
Within Subjects				
Treatment	5.35	4	1.338	54.78*
Residual	1.66	68	0.024	
VAS Scores				
Between Subjects	6.59	24	0.275	
Within Subjects				
Treatment	3.41	4	0.852	30.56*
Residual	2.68	96	0.028	

[a] 7 of 25 cases were excluded with missing values

*$p < .05$

Table 10. The Tukey Test for Post-hoc Multiple Comparisons of Means of EMS-induced Isometric Knee Extension Torques and VAS Scores

Pulse Duration (μs) (Mean)	2	3	4	5
EMS-induced Isometric Knee Extension Torques				
1. 200 (0.199)[a]	*	*	*	*
2. 400 (0.371)		*	*	*
3. 600 (0.674)				
4. 800 (0.802)				
5. 1,000 (0.807)				
VAS Scores				
1. 200 (0.103)[b]	*	*	*	*
2. 400 (0.368)			*	*
3. 600 (0.488)				
4. 800 (0.525)				
5. 1,000 (0.555)				

Note. Critical difference for the means of EMS-induced Isometric Knee Extension Torque was 0.145 Nm/mA (The critical value of the studentized range statistic was $_{.95}q_{68,5} \approx {}_{.95}q_{120,5} = 3.98$). Critical difference for the means of VAS Score was 0.133 $x10^{-1}$ cm/mA (The critical value of the studentized range statistic was $_{.95}q_{96,5} \approx {}_{.95}q_{120,5} = 3.98$).

[a] Unit in Nm/mA. [b] Unit in $x10^{-1}$ cm/mA.

* $p < .05$

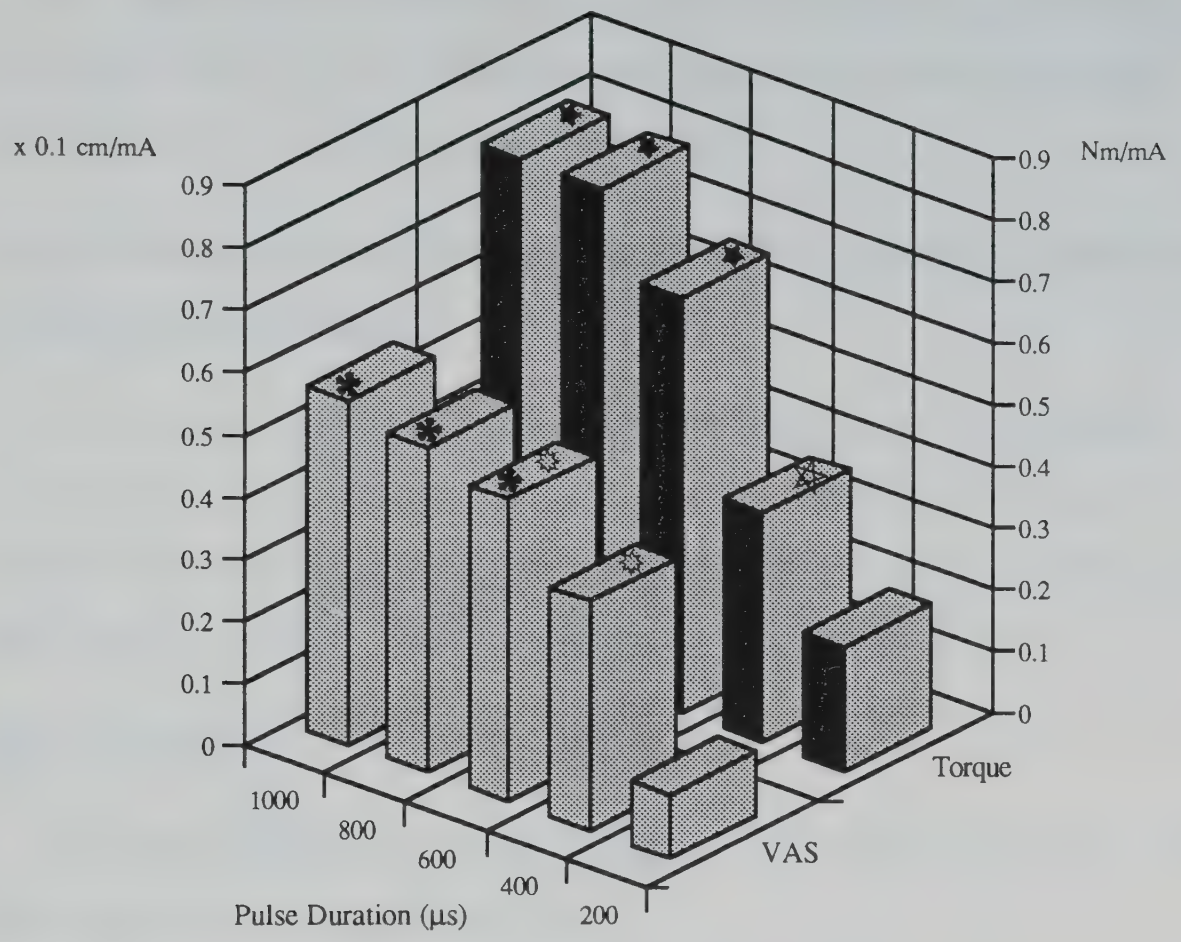


Figure 12. Comparison of Means of EMS-induced Isometric Knee Extension Torques and VAS Scores.

(Means with the same symbol were not significantly different at $p < .05$, means with different symbols were significantly different at $p < .05$, and means with and without symbol(s) differed significantly at $p < .05$)

Optimal Pulse Duration

No optimal pulse duration could be determined because pulse durations (600, 800, and 1,000 μs) which generated higher torque were associated with higher perceived discomfort (Figure 12).

Relationship between EMS-induced Isometric Knee Extension Torque and Stimulation Current Intensity

The Pearson Product-Moment correlation test (Figure 13) indicated a significant positive correlation ($r = .79, p < .05$) between EMS-induced isometric knee extension torque and adjusted stimulation current intensity in RMS value. Therefore, the third hypothesis was rejected.

Skin Impedance

The mean, standard deviation and range of skin impedance were 1.06, 0.39 and 0.45 - 1.7 MΩ respectively.

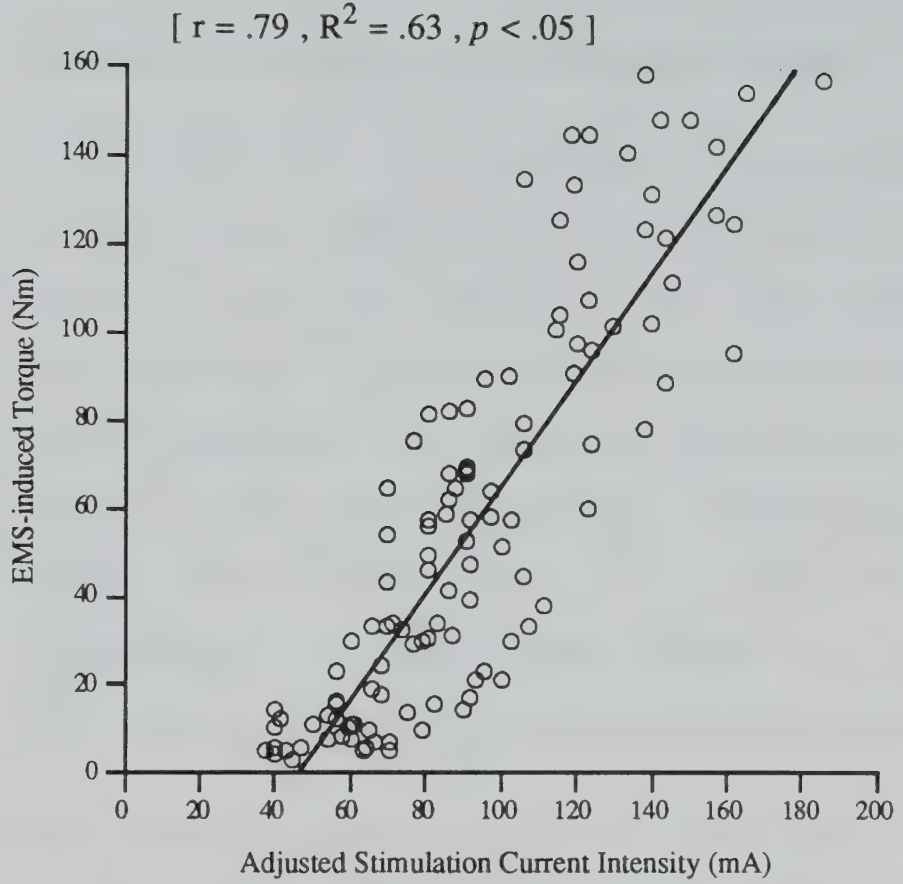


Figure 13. Relationship between EMS-induced Isometric Knee Extension Torque and Adjusted Stimulation Current Intensity.

CHAPTER FIVE

DISCUSSION

Current Intensity - The Ultimate Dosage

The majority of EMS studies have not explicitly documented the type of electrical stimulator used nor calibration of the stimulator. Only Alon et al. (1983), Bowman and Baker (1985), and Kramer et al. (1984) indicated that the type of their stimulators were constant current or constant voltage. For studies in which the calibration of the stimulator has been observed, Gould et al. (1982), Kramer (1987a, 1987b), Kramer et al. (1984), Laughman et al. (1983), Nobbs and Rhodes (1986), and Wolf et al. (1986) measured the maximum current output of the stimulator while Laughman et al. (1983) and Selkowitz (1985) presented the waveform of the stimulation current.

In this study, the accuracy and constancy of the characteristics of stimulation current have been assessed. The waveform, frequency and pulse duration of the stimulation current were accurate and consistent with the designated values. However, the output meter reading of the current intensity of the stimulator was inaccurate. The current output of the stimulator was constant against different resistors only within a range of total current output. However, the current output of the stimulator was constant against human skin throughout the complete range of current output.

Although current intensity was occasionally monitored in some studies (Delitto et al., 1989; Ferguson et al., 1989; Gracanin &Trnkoczy, 1975;

Halbach & Straus, 1980; Owen & Malone, 1983; Stefanovska & Vodovnik, 1985; Morrissey et al., 1985; Wigerstad-Lossing et al., 1988), it was seldom used in determining the dosage of treatments. Methods commonly used to control treatment dosage in EMS studies fell into two categories -- subjective and objective. The subjective means include maximal tolerable current intensity[9], sensory, motor or pain threshold (Alon, 1983, 1985; Balogun, 1986; Erikson & Häggmark, 1979), and strongest visible contraction with minimal discomfort (Romero et al., 1982). The objective means include output meter reading of current intensity (Wigerstad-Lossing et al., 1988), magnitude of EMS-induced torque (Baker et al., 1988; Baker, Cornell, et al., 1989; Baker, McNeal, et al., 1989; Bowman & Baker, 1985), magnitude of EMS-induced torque in terms of percentage of MVIC (Currier & Mann, 1983; Delitto & Rose, 1986; Kubiak et al., 1987; Lai et al., 1988; McMiken et al., 1983; Soo et al., 1988) and range of EMS-induced movement (Vodovnik et al., 1965).

The subjective means are open to individual interpretation and may subsequently lead to high intertrial and intersubject variability of the outcome measurements. Both subjective and objective means were unable to determine or control the dosage (i.e. actual current intensity) that a subject received. Using the subjective or objective means in attempting to control the dosage of EMS treatment among subjects and trials was analogous to using physical signs instead of quantities of drugs to control the dosage of

---

[9] Arvidsson et al., 1986; De Domenico & Strauss, 1986; Delitto et al., 1989; Fahey et al, 1985; Ferguson et al., 1989; Hartsell, 1986; Kramer, 1987a, 1987b; Kramer et al., 1984; Laughman et al., 1983; Mohr et al., 1985, 1986; Morrissey et al., 1985; Reisman, 1984; Selkowitz, 1985; Strauss & De Domenico, 1986; Walmsley et al., 1984; Wolf et al., 1986.

drugs administered to subjects in a study comparing the effectiveness of different drugs in treating a disease. By and large, the current intensity was the ultimate dosage which should be controlled or manipulated in EMS studies in order to improve credibility of the results of EMS studies.

Despite the attempt of equalizing the current intensity among different pulse durations by setting the output meter reading of current intensity constant in this study, the problem of unequal dosage (i.e. current intensity) among treatment groups (i.e. pulse durations) was still unsolved because the current intensity varied concurrently with pulse durations. Although the effect of different current intensity on the two dependent variables (i.e. EMS-induced isometric knee extension torque and VAS Score) among pulse durations had been neutralized by mathematical means, the effect of interaction between current intensity and pulse duration on the outcome measurement remained obscure. This obscurity was further attributed to (1) technical infeasibility of the stimulator to vary pulse duration and current intensity independently and (2) the present study was not designed to investigate the interaction effect between pulse duration and current intensity.

Using current output meter readings of the stimulator to standardize current intensity among pulse durations has two intrinsic problems -- (1) the current output meter reading was inaccurate and (2) the actual current intensities at two pulse durations were different for the same current output meter reading. There were two options, which were by no means exclusive, for monitoring the actual current intensities at different pulse durations. In the first option, a multimeter could be incorporated in the circuit for the direct measurement of output current of the stimulator. This option required

additional manpower to operate and was rejected due to manpower constraints. In the second option, an indirect prediction of current intensity was made by using the regression equations generated from the calibration of the stimulator against human skin. It was the second option in which this study chose to monitor actual current intensities at different pulse durations. Although the regression equation was based on two subjects' results, the almost identical results (Figure 11) endorsed the indirect method for monitoring the current intensity among different pulse durations.

Stimulator

Interestingly, the skin impedance perceived by the multimeter and the stimulator was discrepant. The stimulator would stop functioning if it perceived the skin impedance to be as high as recorded by the multimeter. Owing to the stimulator's built-in safety mechanism, it would automatically shut off if the skin impedance was greater than 5 KΩ. The discrepancy in skin impedances measured with the stimulator and the multimeter might have been attributed to the different construction of the two machines. However, the discrepancy was not a concern in this study as the stimulator was believed to perform linearly and consistently against different skin impedances as illustrated in Figure 11.

As illustrated in Figure 10, the stimulator stopped generating constant current against high resistance. The explanation for this phenomenon is unknown. However, this phenomenon is believed to act as a safety function

of the stimulator in order to prevent the possible damage to human skin at the presence of high current and high resistance (Power = I^2R).

EMS-induced Isometric Knee Extension Torque

In this study, the pulse durations of 600, 800, and 1,000 μs were found to generate significantly higher torques than those of 200 and 400 μs. These findings correlated with those of Hultman et al.'s (1983) study. The differences between the two studies were that Hultman et al. (1983) used a constant voltage stimulator and expressed EMS-induced isometric knee extension torque in terms of percentage of the MVIC. Hultman et al. (1983) also reported that a plateau of EMS-induced torque was reached with a duration of 1,000 μs (Figure 7). The result of this study also revealed that the increase of EMS-induced torque from 800 μs to 1,000 μs was minimal (Figure 12). Further increase of pulse duration would only induce greater perceived discomfort without additional increase of EMS-induced torque (Hultman et al., 1983).

The results of Alon et al.'s (1983) and the present studies are antagonistic. Alon et al. (1983) suggested that 20 to 200 μs was preferable for motor response generation because these pulse durations required less pulse charge to produce the same motor response. In the present study, 200 μs generated less torque than other pulse durations per unit current (mA). In short, the 200 μs was less efficient in torque production than 600, 800, or 1,000 μs. The reason for the different findings between the two studies was unclear. However, Alon et al. (1983) stimulated elbow extensors in six

subjects and their measurements were therefore more susceptible to individual variations because studies with small number of subjects are vulnerable to extreme means. In addition, Alon et al. (1983) used an unorthodox method of analysis in which no inferential statistics were used. Replication of the study concerning the effect of pulse duration on torque production was therefore warranted.

In this study, the longer pulse durations were more effective in torque production. Two possible physiological explanations are that (1) longer pulse duration was more effective in depolarizing the motor fiber and (2) shorter interpulse interval (mediated as frequency) might allow better fusion of muscle twitches, thereby producing a stronger tetanus contraction. Further studies involving the two factors (i.e. pulse duration and interpulse interval) are recommended.

The rival explanation of different current intensities causing discrepancies of EMS-induced torques among pulse durations cannot be ruled out in this study. The current intensity of longer pulse durations, which was higher than that of shorter pulse durations, was able to flow deeper in the muscle and subsequently recruited more motor units to contract simultaneously.

As mentioned in Chapter One, the basic interpretation of the S-D curve was that higher current intensity [higher current output meter reading] was required at shorter pulse durations to reach the same motor response. This study showed that the actual current intensity dropped with a decrease in pulse duration for a set current output meter reading. It seems logical that

higher current intensity [higher current output meter reading] was required at shorter pulse duration to reach the same motor response.

In the present study, EMS-induced isometric knee extension torque at maximal tolerable current intensity (i.e. at 1,000 μs) was lower than MVIC. Interestingly, the majority of subjects believed that their EMS-induced torques were stronger than MVICs. A model was established to attempt to answer these phenomena. For a MVIC, not all motor units of the contracting muscle were recruited at tetanus frequency (Åstrand & Rodahl, 1986). The motor units were recruited in turn throughout the contracting muscle, therefore the tension was evenly distributed in the muscle. For an EMS-induced contraction of the quadriceps, all motor units in the superficial and middle layers of the muscle were recruited to generate the force comparable to MVIC. The total number of motor units recruited in EMS-induced contraction was less than that of MVIC. However, the tension per unit cross sectional area of contracting portion of the muscle in EMS-induced contraction was higher than that of MVIC. The high tension in the superficial and middle portions of the electrically contracted muscle caused intense firing from sensory receptors in the vicinity and subsequently gave a stronger sense of muscle contraction. This model did not hold true in EMS-induced contractions of small muscles such as wrist extensors because these muscles were so small that the stimulation current was able to recruit all the motor units resulting a contraction with the magnitude comparable to a MVIC. Further research is therefore warranted for validating this model.

Selkowitz (1989) indicated that stabilization was necessary in EMS to prevent a loss in measured torque because of the electrically stimulated

muscle shortening from both attachments. Under volitional contraction, the body was stabilized by passive (e.g. lap belt) and active (e.g. synergists) means. In contrast, the body was only stabilized with passive means in EMS-induced contraction. The less effective stabilization in EMS-induced contraction thus might hinder the EMS-induced torque from reaching or passing 100% MVIC.

Perceived Discomfort

Stimulation current with pulse duration at 200 μs was found to induce significantly less discomfort than that of 400, 600, 800, or 1,000 μs in this study. Pulse duration of 400 μs also induced less discomfort than 800 and 1,000 μs. However, there was no difference in perceived discomfort between 400 and 600 μs, and 800 and 1,000 μs. The present results were in agreement with Bowman and Baker's (1985), Gracanin and Trnkoczy's (1975) and Vodovnik et al.'s (1965) studies. They all reported that pulse duration of 300 μs was more comfortable than other pulse durations used in their studies.

The subjects in the present study rated the sensations caused by different pulse durations together with different current intensities. The present research design was not superior to those used in the foregoing studies. Until one is able to vary pulse duration and current intensity independently, one cannot elucidate the result from the possible interaction effect of pulse duration and current intensity.

Apparently, increasing pulse duration (and current intensity) recruits more small pain fibers, thereby resulting in more intense discomfort. However, the majority of subjects in this study indicated that it was not the cutaneous sensation that limited further uptake of stimulation current but rather the intense sense of muscle contraction. Some subjects also expressed concern that the sense of contraction was so intense that they were afraid of structural damage of the muscle. The strong sense of muscle contraction has been explained with the model proposed in the previous section.

The subjects in this study were also asked to rate the perceived discomfort at 1,000 μs at which maximal tolerable current intensity was delivered. It was reasonable to assume that subjects would rate the perceived discomfort at 1,000 μs as maximum if they had taken maximal tolerable current intensity. However, no ratings of perceived discomfort at 1,000 μs were maximum. The mean and standard deviation of this rating was 6.22 ± 2.55 cm. Apparently, the subjects were inclined to rate the perceived discomfort towards sensory discomfort rather than discomfort caused by strong muscle contraction. A separate rating scale for discomfort caused by strong muscle contraction might be worthwhile in further EMS studies.

Optimal Pulse Duration

An optimal pulse duration was not found in this study. Pulse durations of 600, 800, and 1,000 μs generated higher torques but were associated with stronger perceived discomfort (Figure 12). Apparently, pulse durations of 600, 800,and 1,000 μs were more efficient in generating torque per unit current (mA). Pulse duration of 200 and 400 μs induced less discomfort. However, they were not given the chance to perform at a higher actual current intensities comparable to that of 600, 800, and 1,000 μs in this study. Caution should therefore be taken when interpreting the results which might have been concealed with the interaction effect of pulse duration and stimulation current intensity.

Relationship between EMS-induced Isometric Knee Extension Torque and Stimulation Current Intensity

In this study, a significant linear correlation ($r = .79$, $p < .05$) was found between EMS-induced torque of the quadriceps muscle and stimulation current intensity, therefore, the third hypothesis was rejected. This finding was incongruous with the results of Kubiak et al.'s (1987), Laughman et al.'s (1983), and Selkowitz's (1985) in which they reported no consistent correlation between the stimulation current intensity and the resulting muscle torque. The reason for this incongruity is obscure. Two other studies (Baker, 1981; De Domenico & Strauss, 1987) described the relationship between EMS-induced torque and stimulation current intensity

as S-shaped and curvilinear respectively. One of the possible explanations for the foregoing nonlinear relationships is that Baker (1981) might have used a stimulator whose current intensity was front loaded, thereby giving a S-shaped curve (Figure 2) while De Domenico and Strauss (1987) might have used an end loaded stimulator resulting in a curvilinear relationship. The stimulator in the present study generated linear output current (Figure 11), thereby producing a linear relationship between the EMS-induced torque and stimulation current intensity.

One might argue that the variance of EMS-induced torque was too large (Figure 13). The large variance of EMS-induced torque might be attributed to the following:

1 The variance of volitional muscle torque has been documented in the order of ± 10% or even higher (Tornvall, 1963; Simonson, 1971), therefore not surprisingly so the EMS-induced torque was as well.

2 The effective current intensity that reached the muscle fibers and motor nerves might vary among subjects. The effective current intensity might depend on (a) the amount of subcutaneous adipose tissue, (b) the amount of non-contractile component in the stimulated muscle, and (c) the amount and distribution of different muscle fiber types and their motor nerves. These factors could have subsequently affected the EMS-induced torque.

3 The current density along the stimulated muscle were different among subjects. This current density depended on the relationship between the electrode surface area and the muscle surface area. Under the conditions of equal electrode size and stimulation current intensity, the subject with a higher ratio of electrode surface area to muscle surface area might yield a higher EMS-induced torque. Since the muscle surface area varied among subjects, so would the EMS-induced torque.

The foregoing explanations for the large variance of EMS-induced torque warrant further studies.

Apparently, the significant positive linear relationship between the EMS-induced torque and stimulation current intensity supported the basis of Kots' claim that high stimulation current intensity was associated with high EMS-induced torque and subsequently high training effect within the current intensity range tested in this study.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

Summary

The purposes of the study were (1) to determine the pulse duration(s) which produced the greatest EMS-induced isometric knee extension contraction, (2) to determine the pulse duration(s) which induced the minimal perceived discomfort, (3) to determine the optimal pulse duration(s) which produced maximal EMS-induced torque with minimal perceived discomfort, and (4) to determine the relationship between stimulation current intensity and magnitude of EMS-induced contraction.

The research design of the study was repeated measures over pulse durations. Twenty-five male physical therapy students volunteered in the study in which their right quadriceps muscles were stimulated with the constant current stimulator at five pulse durations. The two dependent variables were the EMS-induced torque and perceived discomfort which were measured with the dynamometer and VAS scale respectively.

When the calibration of the stimulator, the current output meter reading of the stimulator was found inaccurate at any pulse duration. In addition, the actual current outputs of the stimulator were different among the five pulse durations regardless of the same current output meter reading among the five pulse durations. The current output of the stimulator was adjusted to the actual current output with calibration equations (i.e. regression equations).

The threat of the extraneous variable of different current intensities among pulse durations was neutralized by standardizing the two dependent variables with the corresponding actual current intensities.

The three hypotheses tested in the study were rejected. There was difference in the magnitude of the EMS-induced isometric knee extension contraction and the perceived discomfort score among the five pulse durations. The magnitude of EMS-induced isometric knee extension contraction was linearly related to the stimulation current intensity. Further, no optimal pulse duration was determined in the study.

Recommendations

The following recommendations are suggested:

1 Separate rating scales for the sensory discomfort and discomfort caused by strong muscle contraction should be used.

2 The extraneous variable of current intensity should be either

(a) controlled in the research design by making a prototype constant current stimulator which is able to keep output current constant irrespective of variations in other current characteristics--pulse duration, frequency and waveform at a set current output meter reading, or

(b) built in a study by using factorial design which would enable one to explore the interaction effect among various current characteristics.

3 Further research needs to be done in the following areas:

(a) investigating the physiological explanations that the longer pulse durations were more effective in torque production.

(b) validating the model suggested in this study in explaining the mode of EMS-induced contraction.

(c) verifying the explanations on the large variance of EMS-induced torque.

Clinical Implications

Selection of pulse duration should depend on (1) the type of patient and (2) the patient's discomfort tolerance.

For normal subjects, inducing torque close to the maximum force-generating capacity of the stimulated muscle is the prime objective. Therefore, pulse durations of 600, 800, or 1,000 μs are recommended.

For patients with moderate to high discomfort tolerance, a pulse duration of 400 μs is advised to provide a good contraction with modest discomfort. The pulse duration should be increased with the positive progression of the condition.

For patients with low discomfort tolerance, a pulse duration of 200 μs is appropriate to provide a reasonable contraction without 'excessive'

perceived discomfort by the patients. When patients have less fear about EMS, longer pulse duration may be used.

Figure 11 illustrates that the rate of actual current output increase at longer pulse durations is greater than that of shorter pulse durations for the same increment of output meter reading. For EMS, the increment of current output meter reading should be modest at long pulse durations to avoid startling the patients.

Conclusions

Within the limitations of this study, the following conclusions may be stated:

1 Stimulation currents with pulse durations of 600, 800, and 1,000 μs generated a stronger torque per unit current (mA) than that of 200 and 400 μs. Stimulation currents of 400 μs generated a stronger torque than that of 200 μs.

2 Stimulation currents with pulse durations of 200 μs induced less perceived discomfort per unit current (mA) than that of 400, 600, 800, and 1,000 μs. Stimulation currents of 400 μs induced less discomfort than 800 and 1,000 μs, but there was no difference between 400 and 600 μs.

3 Higher stimulation current intensity yielded stronger EMS-induced torque.

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Appendix A

Consent Form

The University of Alberta
Department of Physical Therapy

CONSENT FORM

THE EFFECT OF PULSE DURATION ON ISOMETRIC KNEE EXTENSION TORQUE AND PERCEIVED DISCOMFORT

Outline of Procedures (retained by subject)

Electrical muscle stimulation (EMS) is an effective means for improving muscle strength. EMS is the application of an electrical stimulus of sufficient intensity and duration to muscle and/or nerve resulting in a muscle contraction. Perception of discomfort associated with EMS is commonly reported. Pulse duration is one of the current characteristics which may influence the intensity of perceived discomfort associated with EMS and the effectiveness of EMS in improving muscle strength. The purpose of this study is to determine the optimal pulse duration(s) that produce maximal electrical induced knee extension (or straightening) force with the least perceived discomfort.

The study in which you are being requested to participate will compare the electrical induced knee extension force by electrical currents of different pulse durations. You will be seated, your body and thighs secured to the testing chair and your thigh muscles will be stimulated with a commercially available electrical stimulator. All electrical induced contractions, which are not longer than 12 s, will be of an isometric (no movement) nature.

You will be required to participate in a practice session prior to the actual testing session. The two sessions will be a week apart to allow complete recovery from the possible feeling of tiredness resulted from the practice session. When electrical induced muscle contractions are to be performed, one electrode will be placed in the groin area covering the femoral nerve while the other electrode will be positioned on the front of your thigh covering the quadriceps muscles just above the knee cap. The current intensity will be gradually increased by the investigator in both sessions to the predetermined level. On both occasions, you will be provided with a safety switch to terminate the current any time at your own will.

The electrical stimulus will at first give a sensation on the skin which may vary from individual to individual. As the stimulation intensity increases, you will begin to feel the thigh muscles contract with greater and greater force. However, the feeling of the electrical induced contraction will be similar to that which you have experienced in traditional resisted exercise and in electrotherapy classes. You will be required to rate your perception of discomfort associated with EMS at the predetermined level on a chart after each electrical induced contraction. A total of five electrical induced knee extensions will be tested.

There will be one intensity of electrical stimulus used which is the intensity you can maximally tolerate and this intensity will be determined during the testing session. The current intensity utilized during this study is far below that obtained from normal household current. The electrical stimulator has been inspected by the Canadian Standards Association, and the investigator is familiar with EMS techniques. You will be notified as to when the stimulus is to commence or end.

As a result of the high muscular contraction forces involved, there exists a possibility of muscular discomfort during and after the testing session. However, this discomfort should be absent or minimal, in most cases, and, if experienced, should be similar to that experienced during and after routine vigorous exercise.

The length of the two sessions will not be longer than an hour each. No records or photographs which would permit your identification will be made public or used in any medical article without your permission. In the event of questions, please feel free to contact Mr. Aaron Wan (439-6797) or Dr. David Magee (492-5984). You have the right to withdraw from participation at any time without prejudice to you.

The University of Alberta
Department of Physical Therapy

CONSENT FORM

THE EFFECT OF PULSE DURATION ON ISOMETRIC KNEE EXTENSION TORQUE AND PERCEIVED DISCOMFORT

Subject Consent (retained by investigator)

I, _____, freely and voluntarily consent to participate in a study under the direction of Mr. Aaron Wan, Graduate Student, and Dr. David Magee, Professor, Department of Physical Therapy, University of Alberta.

A thorough description of the procedures has been explained, and I understand the potential risks involved. I have been informed of the various contraindications which would keep me from participating in this study. These contraindications include cardiac problems and pacemakers.

I understand if I have any questions regarding my participation in this study, I may call Mr. Aaron Wan at 439-6797 or Dr. David Magee at 492-5984. I also understand that I may withdraw my consent and discontinue participation in this study at any time without prejudice to me.

I authorize Mr. Aaron Wan, Dr. David Magee, and the Department of Physical Therapy to keep, preserve, use and dispose of the findings from this study with the provision that my name will not be associated with any of the results.

I have been given the right to ask, and have answered, any questions concerning the procedures to be used during this study. Questions have been answered to my satisfaction. With my signature below, I indicate that I understand all that is required of me in this study, and I acknowledge receipt of a copy of this consent form.

_____ _____
Participant's signature Witness' signature

_____ _____
Date Date

I have explained and defined in detail the study procedure to which the subject has consented to participate.

_____ _____
Investigator's signature Date

Appendix B

Calibration of KIN/COM™ Isokinetic Dynamometer

1. Select Exercise Program from the KIN/COM™ Program Menu.

2. Select "UTILITY" and then move cursor to "CALIBRATION MODE". Press <ENTER>. [The voice synthesizer (VS) will say "calibration mode, remove all attachments"]

3. Remove the attachment arm and load cell slider block assembly from the output shaft of the module and place them on the table of the machine so as not to cause a load or force to be exerted on the load cell. If a load is present, the VS will repeat the above request [during the calibration routine] until the load cell has no force acting on it.

4. Press <ENTER>. The main motor will start and the output shaft will go through a preprogrammed calibration and test routine. When calibration is complete, the VS will announce "calibration complete". Press <ESC> for the EXERCISE MODE.

5. Install attachment arm onto the output shaft on the desired side of the machine.

Appendix C

Specifications of KIN/COM™ Dynamometer

Maximum Velocity:	230^0/s
Maximum Force:	2100 N
Maximum Angular Displacement:	270^0
Resolutions:	
Force	± 4 N
Position	± 1^0
Velocity	2.5% of range

Appendix D

Specifications of Electrical Stimulator--UltraStim®

Output	Constant current , maximum output 200 volts at 99 mA each channel indepenently adjustable for on time, ramp up time , ramp down time
Pulse Waveforms[a]	B S Square , U Square , U Triangular , Mod High Frequency
Pulse Frequency	Adjustable 1-99 Hz ; 1200-2200 Hz
Phase Width	Adjustable 10-500 μs for B S Square
Ramp Up & Down	Adjustable 0-9.9 s
Maximum Output	Adjustable 0-99 mA for B S Square
Interpulse Delay	Adjustable 40-990 μs for B S Square
Power Source	One or two 9 volt alkaline or rechargeable batteries
Mechanical Dimensions	5.375 in x 3.375 in x 1.375 in

[a] B : bidirectional ; S : symmetrical ; U : unidirectional ; Mod : modulated.

Appendix E

Application Order of Pulse Duration for Subjects

	Application Order of Pulse Duration				
ID	1st	2nd	3rd	4th	5th
1	3	2	4	5	1
2	1	3	2	5	4
3	1	2	4	3	5
4	3	1	5	2	4
5	3	4	1	2	5
6	2	4	3	5	1
7	2	1	3	5	4
8	4	1	5	2	3
9	4	3	5	2	1
10	1	2	4	3	5
11	5	2	3	1	4
12	2	5	3	1	4
13	2	4	3	1	5
14	1	5	3	4	2
15	1	3	5	2	4
16	4	2	3	1	5
17	2	5	1	3	4
18	5	2	1	3	4
19	3	1	5	4	2
20	5	2	1	3	4
21	4	5	1	2	3
22	4	3	1	2	5
23	3	1	4	2	5
24	3	2	4	5	1
25	1	4	3	5	2

Note. 1 : 200μs ; 2 : 400μs ; 3 : 600μs ; 4 : 800μs ; 5 : 1,000μs.

Appendix F

Descriptive Statistics of EMS-induced Isometric Knee Extension Torque and VAS Score

	EMS-induced Torque (Nm/mA)				
	200 μs	400 μs	600 μs	800 μs	1,000 μs
Mean	0.19	0.37	0.67	0.80	0.81
Standard Deviation	0.12	0.24	0.31	0.27	0.23
Range	0.06 - 0.48	0.08 - 0.89	0.12 - 1.26	0.18 - 1.21	0.28 - 1.14
	VAS Score (x 10^{-1} cm/mA)				
Mean	0.10	0.37	0.49	0.53	0.56
Standard Deviation	0.18	0.31	0.31	0.28	0.29
Range	0.00 - 0.72	0.00 - 1.01	0.00 - 1.07	0.03 - 1.13	0.02 - 1.02

Appendix G

Raw Data from Familiarization and Testing Sessions

ID	AGE	HT	WT	Ω	MVIC	MAXI
1	31	1.68	67.8	1.40	127.3	45
2	29	1.75	69.5	0.71	173.7	60
3	24	1.77	76.5	1.70	164.1	38
4	25	1.78	68.0	1.70	137.0	70
5	26	1.78	71.3	1.47	130.6	52
6	24	1.85	81.8	1.28	155.1	58
7	25	1.83	77.3	1.10	158.1	60
8	22	1.80	79.5	1.47	183.8	65
9	22	1.72	61.4	0.97	111.9	40
10	21	1.80	77.3	1.60	160.8	68
11	19	1.80	77.0	0.85	174.9	80
12	20	1.88	87.0	1.06	216.6	70
13	25	1.80	84.5	0.85	135.9	47
14	29	1.75	86.4	0.84	144.1	43
15	19	1.78	71.5	-	156.2	40
16	19	1.78	75.0	1.45	166.5	45
17	32	1.68	75.0	0.66	136.3	50
18	24	1.83	85.2	0.63	211.1	60
19	22	1.95	86.2	-	209.6	40
20	23	1.85	83.0	0.62	146.7	63
21	23	1.68	89.8	1.24	150.2	40
22	28	1.88	81.6	0.56	208.8	68
23	24	1.78	86.2	0.56	133.2	42
24	26	1.69	59.9	1.25	90.5	40
25	27	1.67	56.0	0.45	95.9	38

ID	EMS1	EMS2	EMS3	EMS4	EMS5	VAS1	VAS2	VAS3	VAS4	VAS5
1	-	-	29.4	46.8	56.7	0	5.05	5.85	5.75	7.70
2	7.5	-	43.8	59.1	77.7	0.05	0.40	1.15	2.15	2.70
3	-	12.6	18.7	28.8	67.7	0	0	1.70	5.10	8.55
4	4.8	20.7	74.4	88.2	94.5	0.20	0.15	0.45	0.45	0.35
5	-	-	38.5	73.0	90.1	0.35	0.15	4.35	5.05	2.55
6	7.8	33.0	56.7	144.0	133.2	0.95	3.15	5.90	8.60	7.70
7	10.8	61.5	134.1	144.0	157.5	2.70	5.30	5.80	7.20	6.90
8	9.2	20.5	124.7	140.0	147.6	0.80	1.70	9.10	7.10	6.75
9	3.7	11.8	32.4	55.6	68.1	0	0.30	2.70	3.30	4.20
10	23.7	63.2	115.4	130.7	141.5	0.10	5.05	6.40	6.90	7.60
11	30.0	103.2	147.3	153.6	156.3	0.40	4.95	5.15	6.90	8.05
12	6.3	56.5	95.4	120.3	124.4	0.35	3.75	3.65	3.95	6.40
13	5.2	6.3	15.0	22.9	32.7	0.10	0.20	3.00	1.30	4.10
14	4.7	10.7	13.3	30.7	-	0	2.45	3.75	5.10	7.80
15	9.7	22.7	42.7	56.6	67.5	0.20	4.10	7.20	5.80	8.90
16	2.9	5.2	9.5	16.5	29.0	0	1.25	3.40	3.15	4.80
17	10.4	33.2	64.2	89.7	100.1	0	2.70	1.80	6.10	7.50
18	29.1	40.5	78.6	107.1	123.6	3.00	4.80	3.85	5.50	6.75
19	5.1	-	53.1	48.6	68.7	0.25	3.10	7.50	9.20	7.80
20	4.5	14.0	37.2	100.9	110.7	0	2.65	1.70	6.40	7.10
21	13.7	15.6	63.9	80.8	82.1	0	0	0	0.70	0.60
22	17.1	57.2	96.6	101.4	125.9	0	0.50	3.60	5.20	4.50
23	11.8	10.1	32.1	58.5	89.0	3.00	6.05	6.80	8.60	9.45
24	-	16.0	-	45.2	52.2	0.35	3.90	4.75	6.60	7.90
25	4.5	7.5	32.4	74.5	81.2	0.70	4.85	6.70	7.75	8.85

Note. HT : height in m; WT : weight in kg; Ω : skin impedance in MΩ; MAXI : maximum tolerable current intensity in mA; EMS1,EMS2, EMS3, EMS4, EMS5 : EMS-induced isometric torques at 200, 400, 600, 800, 1,000 μs respectively, in Nm; VAS1, VAS2, VAS3, VAS4, VAS5 : VAS scores at 200, 400, 600, 800, 1,000 μs respectively, in cm.

- : missing value.

Appendix H

Raw Data from the Calibration of the Stimulator

	200 µs	400 µs	600 µs	800 µs	1000 µs	200 µs	400 µs	600 µs	800 µs	1000 µs
			1.1 KΩ					2.2 KΩ		
10	9.3	13.3	16.6	19.1	21.3	9.4	13.2	16.4	19.0	21.0
15	14.1	20.0	24.7	28.6	31.9	14.1	19.9	24.5	28.4	31.6
20	19.4	27.5	33.8	39.2	43.9	19.3	27.3	33.6	38.8	43.6
25	24.4	34.5	42.5	49.2	55.1	24.2	34.3	42.2	48.8	54.7
30	29.4	41.7	51.3	59.5	66.6	29.2	41.5	51.0	59.0	66.3
35	35.0	49.6	61.0	70.8	79.4	34.7	49.3	60.7	70.3	78.8
40	40.1	56.9	70.1	81.3	91.1	39.8	56.6	69.7	80.8	90.5
45	44.6	63.4	78.0	90.4	101.4	44.3	63.0	77.6	89.8	100.7
50	50.1	71.4	88.0	102.0	114.3	49.8	71.0	87.4	101.3	113.5
55	54.8	78.2	96.3	111.7	125.2	54.4	77.5	95.6	110.8	124.1
60	60.5	86.3	106.3	123.4	138.3	60.0	85.6	105.2	121.4	135.7
65	66.6	95.2	117.2	135.8	152.1	65.5	93.1	113.7	129.4	144.0
70	71.0	101.4	124.8	144.5	162.1	68.6	96.9	117.5	131.7	146.2
75	75.6	108.1	133.2	154.1	172.6	70.6	98.6	118.5	132.0	146.8
80	81.5	116.5	143.2	165.6	185.1	70.7	98.6	118.6	132.0	146.9
85	85.7	122.5	150.4	173.6	194.0	70.6	98.6	118.5	132.0	146.9
90	90.7	129.5	158.9	182.7	203.6	70.6	98.6	118.5	131.9	147.0
95	95.4	135.9	166.3	190.6	211.4	70.6	98.6	118.5	131.9	147.1
			3.9 KΩ					4.4 KΩ		
10	9.3	13.1	16.2	18.8	20.9	9.3	13.1	16.0	18.5	20.9
15	13.9	19.7	24.2	28.1	31.4	13.8	19.6	24.1	27.9	31.3
20	19.1	27.0	33.3	38.7	43.2	19.1	27.1	33.1	38.4	43.1
25	23.9	33.9	41.8	48.5	54.3	23.9	33.9	41.5	48.2	54.1
30	28.9	41.1	50.6	58.6	65.6	28.9	40.9	50.3	58.4	65.5
35	34.3	48.8	60.2	69.6	78.1	34.3	48.7	59.8	69.3	77.7
40	39.4	56.0	69.0	79.8	89.3	39.3	55.6	67.4	76.6	85.1
45	43.8	61.7	75.3	84.6	94.4	42.2	57.1	68.1	76.9	85.1
50	46.0	63.2	76.2	84.8	94.6	42.2	57.1	68.1	76.9	85.1
55	46.1	63.2	76.2	84.9	94.6	42.3	57.1	68.1	76.9	85.1
60	46.1	63.3	76.3	84.9	94.5	42.3	57.1	68.2	76.9	85.1
65	46.1	63.3	76.3	84.9	94.4	42.2	57.1	68.2	76.9	85.1
70	46.1	63.3	76.3	84.9	94.5	42.2	57.1	68.2	76.9	85.1
75	46.1	63.4	76.3	84.9	94.4	42.2	57.1	68.2	76.9	85.4
80	46.1	63.4	76.3	84.9	94.4	42.2	57.1	68.2	76.9	85.2
85	46.1	63.4	76.4	85.0	94.3	42.2	57.1	68.2	76.9	85.2
90	46.1	63.4	76.4	84.9	94.2	42.2	57.1	68.2	76.9	85.2
95	46.2	63.4	76.4	84.9	94.3	42.2	57.1	68.2	76.9	85.2
			Subject A					Subject B		
10	9.8	13.5	16.4	19.0	21.4	9.1	13.1	16.2	18.8	21.3
15	14.2	20.2	24.5	28.5	32.1	13.8	19.8	24.5	28.4	31.9
20	19.4	27.6	33.7	39.2	44.1	19.3	27.3	33.7	39.2	43.9
25	24.4	34.7	42.6	49.3	55.5	24.2	34.3	42.4	49.3	55.4
30	29.5	42.0	51.4	59.7	67.7	29.3	41.6	51.3	59.6	66.9
35	35.0	49.7	61.2	71.1	79.7	34.9	49.5	61.2	71.0	79.7
40	40.1	57.3	70.4	81.6	91.5	40.1	56.9	70.3	81.6	91.6
45	44.6	63.8	78.3	90.9	101.9	44.6	63.3	78.2	90.8	101.9
50	50.2	71.8	88.4	102.4	114.9	50.2	71.4	88.2	102.4	114.9

table continued

55	54.3	78.7	96.8	112.2	125.8	54.9	78.2	96.6	112.1	125.8
60	60.7	87.0	107.0	124.0	139.1	60.7	86.4	106.7	123.9	138.9
65	66.6	95.8	117.9	136.4	-	66.8	95.3	117.6	136.3	-
70	71.0	101.4	125.5	145.4	-	71.3	101.6	125.3	145.5	-
75	75.6	108.2	133.8	155.1	-	76.0	108.2	133.6	155.1	-
80	81.5	116.6	144.2	167.4	-	81.8	116.7	144.0	167.2	-
85	85.8	123.0	151.8	-	-	86.0	122.8	151.7	-	-
90	91.0	130.4	161.2	-	-	91.3	130.5	161.0	-	-
95	96.2	137.8	170.4	-	-	96.6	137.9	170.2	-	-

Note. - denotes missing value.

Appendix I

Data of EMS-induced Torque in %MVIC and Adjusted Stimulation Current Intensity

	EMS-induced Torque in %MVIC					Adjusted Stimulation Current Intensity (mA)				
ID	200 μs	400 μs	600 μs	800 μs	1000 μs	200 μs	400 μs	600 μs	800 μs	1000 μs
1	-	-	23.10	36.76	44.54	44.92	64.13	79.02	91.68	102.87
2	4.32	-	25.22	34.02	44.73	60.26	86.12	106.17	123.17	138.15
3	-	7.68	11.40	17.55	41.26	37.76	53.86	66.34	76.98	86.41
4	3.50	15.11	54.31	64.38	68.98	70.49	100.79	124.28	144.16	161.66
5	-	-	29.48	55.90	68.99	52.08	74.39	91.69	106.67	119.33
6	5.03	21.28	36.56	92.84	85.88	58.22	83.19	91.69	118.97	119.33
7	6.83	38.90	84.82	91.08	99.62	60.26	86.12	106.17	123.17	138.15
8	5.01	11.15	67.85	76.17	80.30	65.38	93.46	115.23	133.67	149.90
9	3.31	10.55	28.95	49.69	60.86	39.81	56.79	69.96	81.18	91.12
10	14.74	39.30	71.77	81.28	88.00	68.45	97.86	120.66	139.96	156.96
11	17.15	59.01	84.22	87.82	89.37	80.72	115.46	142.39	165.16	185.17
12	2.91	26.08	44.04	55.54	57.43	70.49	100.79	124.28	144.16	161.66
13	3.83	4.64	11.04	16.85	24.06	46.97	67.06	82.64	95.88	107.58
14	3.26	7.43	9.23	21.30	-	42.88	61.19	75.39	87.48	98.17
15	6.21	14.53	27.34	36.24	43.21	39.81	56.79	69.96	81.18	91.12
16	1.74	3.12	5.71	9.91	17.42	44.92	64.13	79.02	91.68	102.87
17	7.63	24.36	47.10	65.81	73.44	50.04	71.46	88.07	102.17	114.63
18	13.78	19.19	37.23	50.73	58.55	60.26	86.12	106.17	123.17	138.15
19	2.43	-	25.33	23.19	32.78	39.81	56.79	69.96	81.18	91.12
20	3.07	9.54	25.36	66.78	75.46	63.33	90.52	111.61	129.47	145.20
21	9.12	10.39	42.54	53.79	54.66	39.81	56.79	69.96	81.18	91.12
22	8.19	27.39	46.26	48.56	60.30	68.45	97.86	120.66	139.96	156.96
23	8.86	7.58	24.10	43.92	66.82	41.85	59.73	73.58	85.38	95.82
24	-	17.68	-	49.94	57.68	39.81	56.79	69.96	81.18	91.12
25	4.69	7.82	33.79	77.69	84.67	37.76	53.86	66.34	76.98	86.41

Note. - denotes missing value.

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